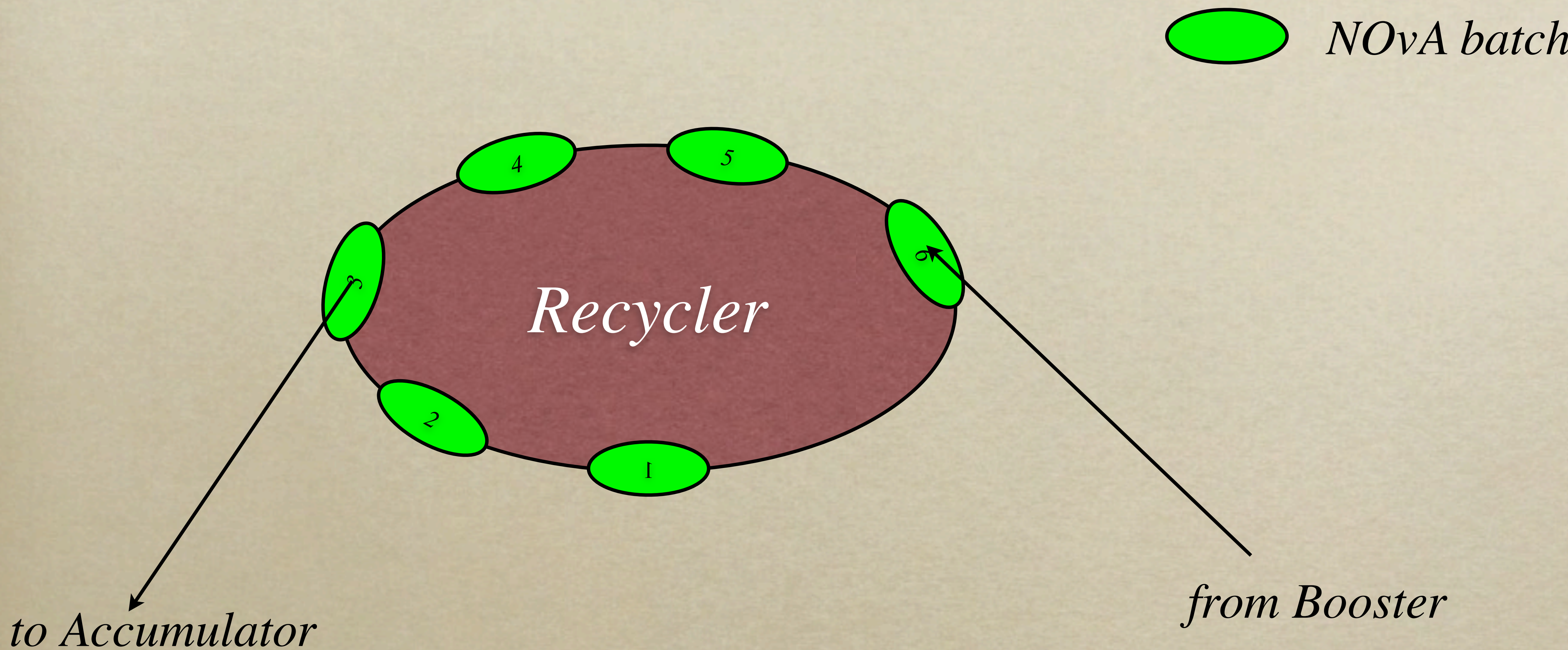
Threading through NOvA

- *Mu2e Baseline proposal has a nice duty factor, but is "constrained" by the available Booster cycles from which to take its beam*
- *Loosen that constraint by allowing beam to "thread" in-and-out through the Recycler's injection gap while beam is circulating that is destined for NOvA**

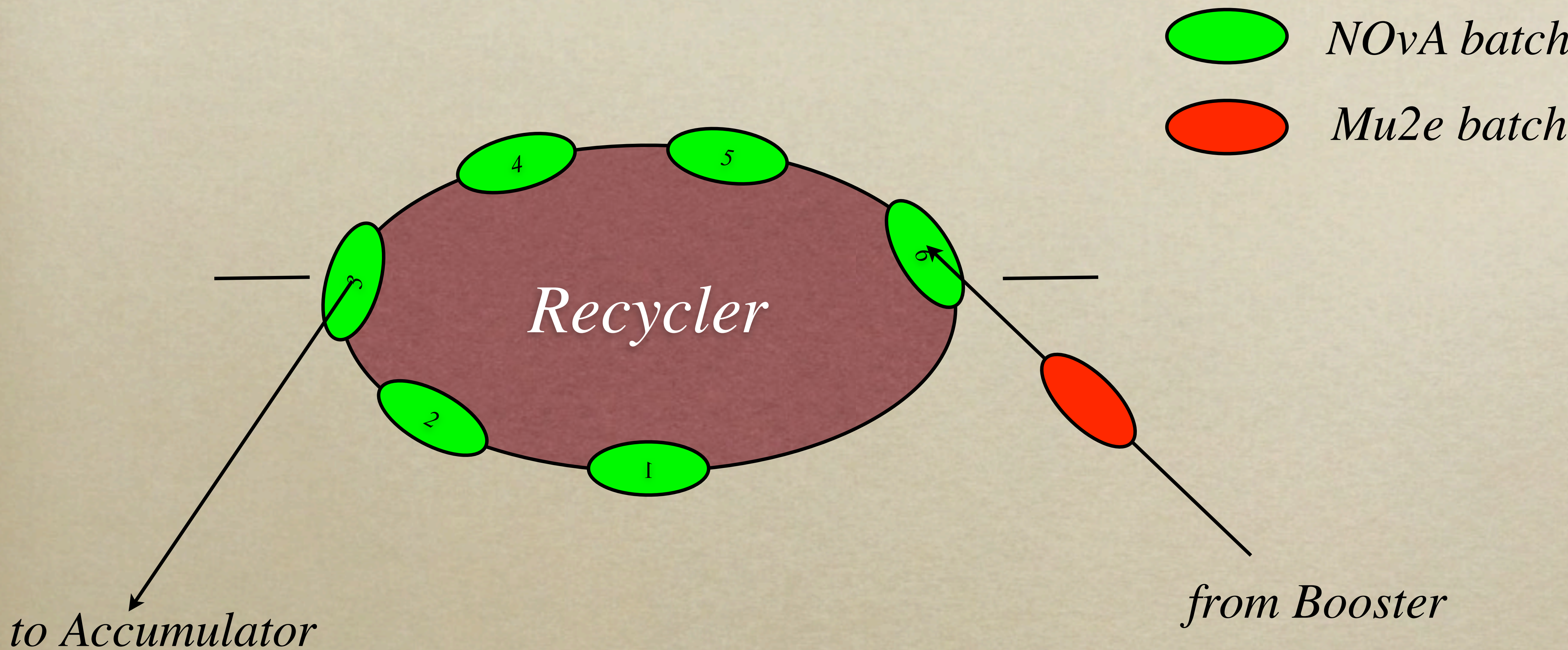
**Original suggestion made by some linear combination of C. Ankenbrandt and M. Popovic*

Threading Mu2e through NOvA

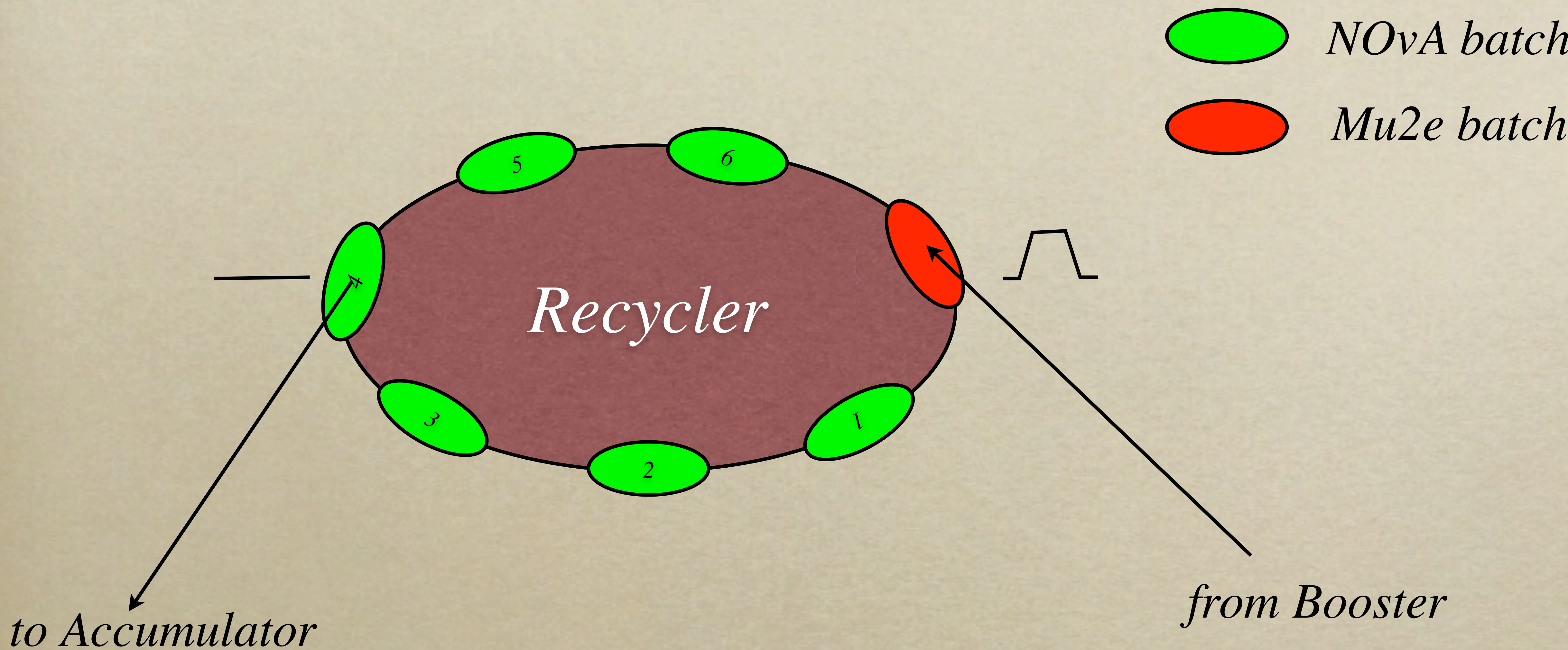


- *Recycler circumference is 7x the Booster*
- *NOvA accepts 6 "batches" from Booster, then performs "slip stacking" to a slightly different energy (and hence different orbit) in order to accept 6 more*
- *Use the existing "gap" to thread beam through toward Mu2e*

Threading Mu2e through NOvA



Threading Mu2e through NOvA



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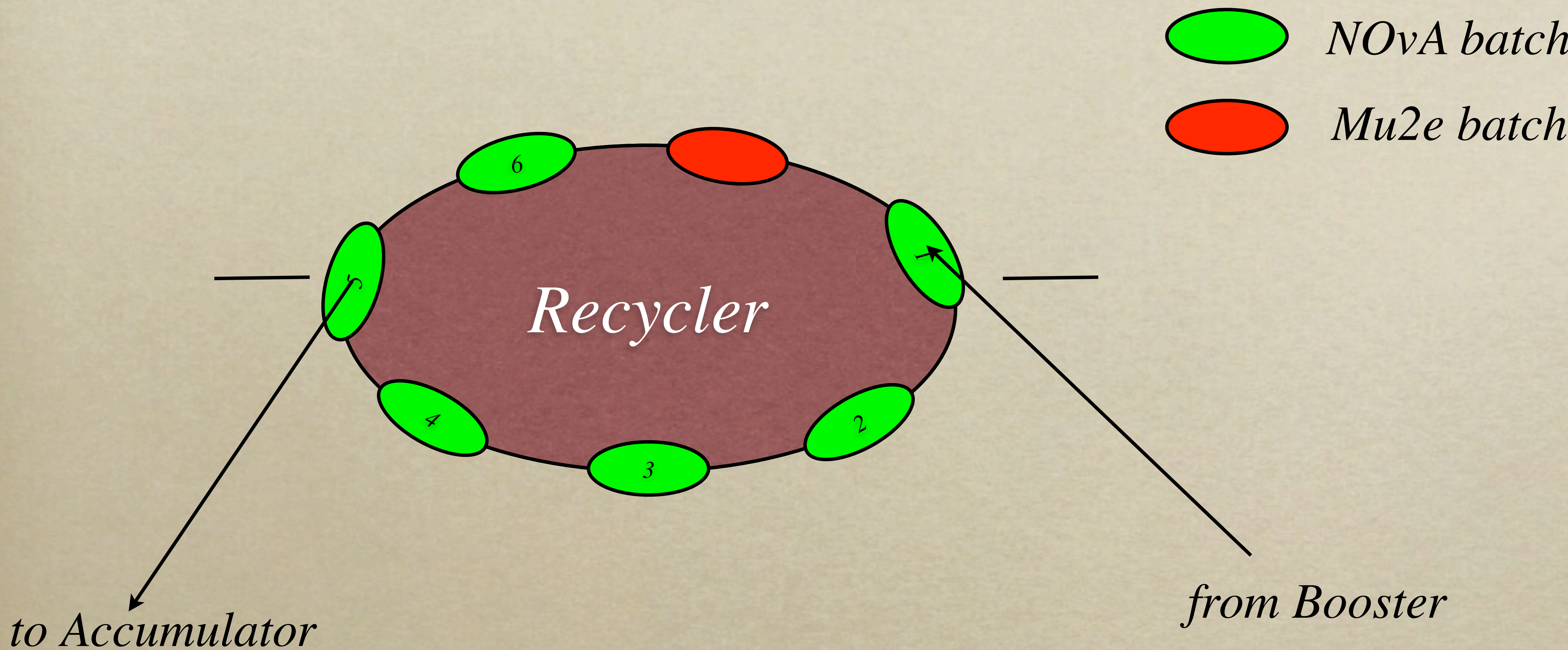
Threading Mu2e through NOvA



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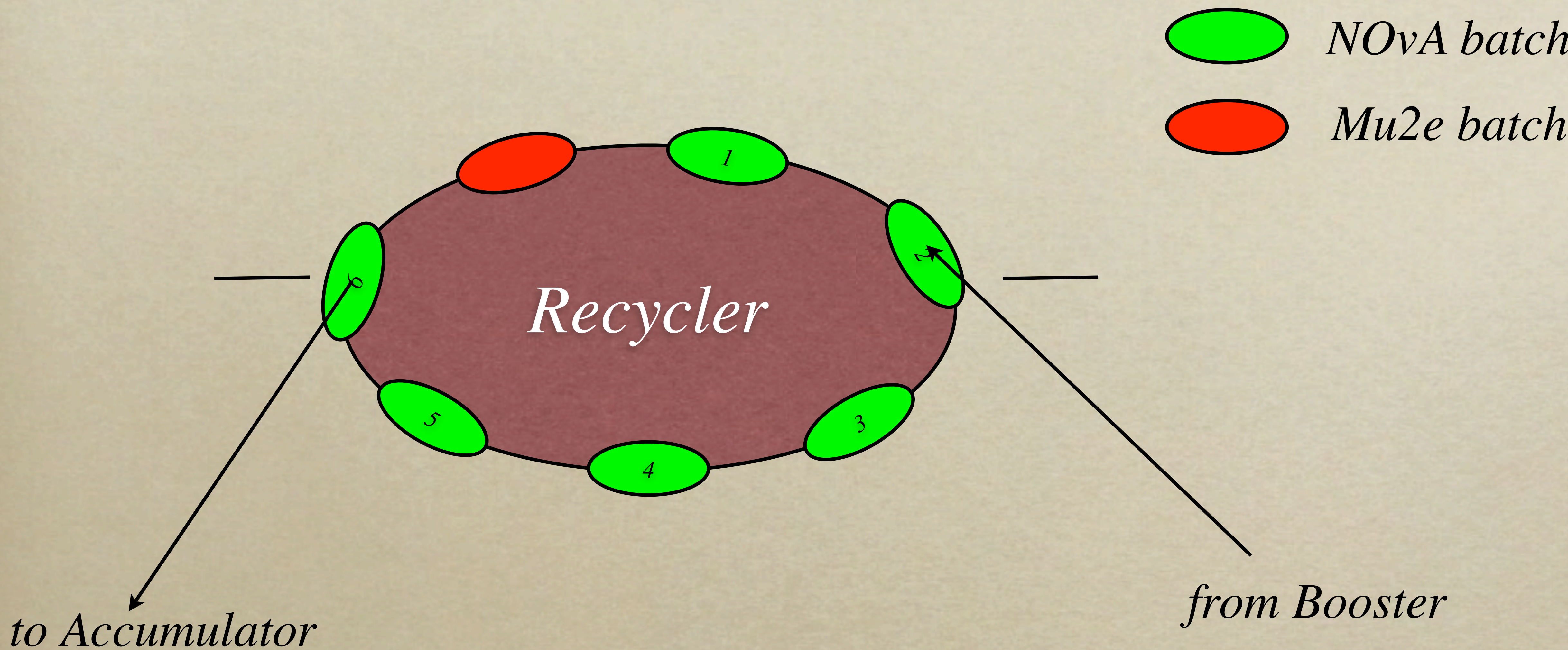
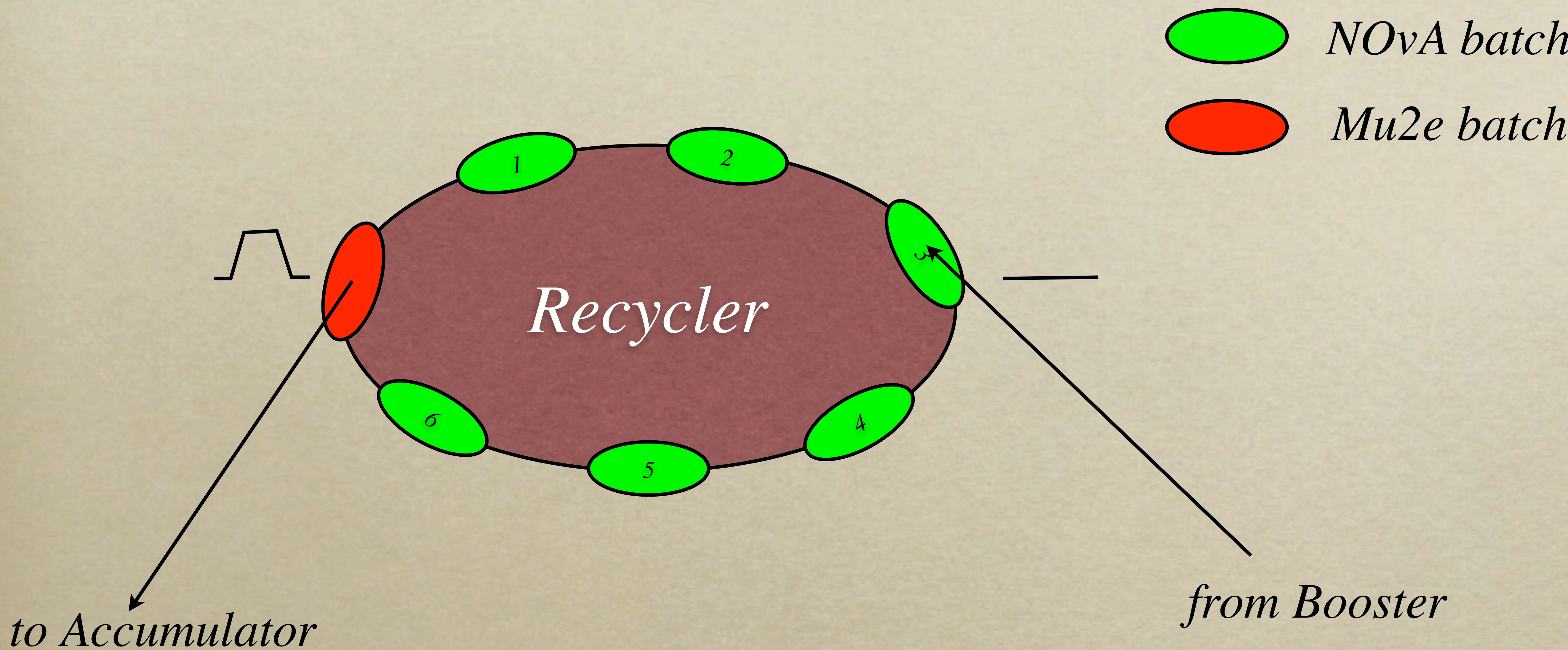
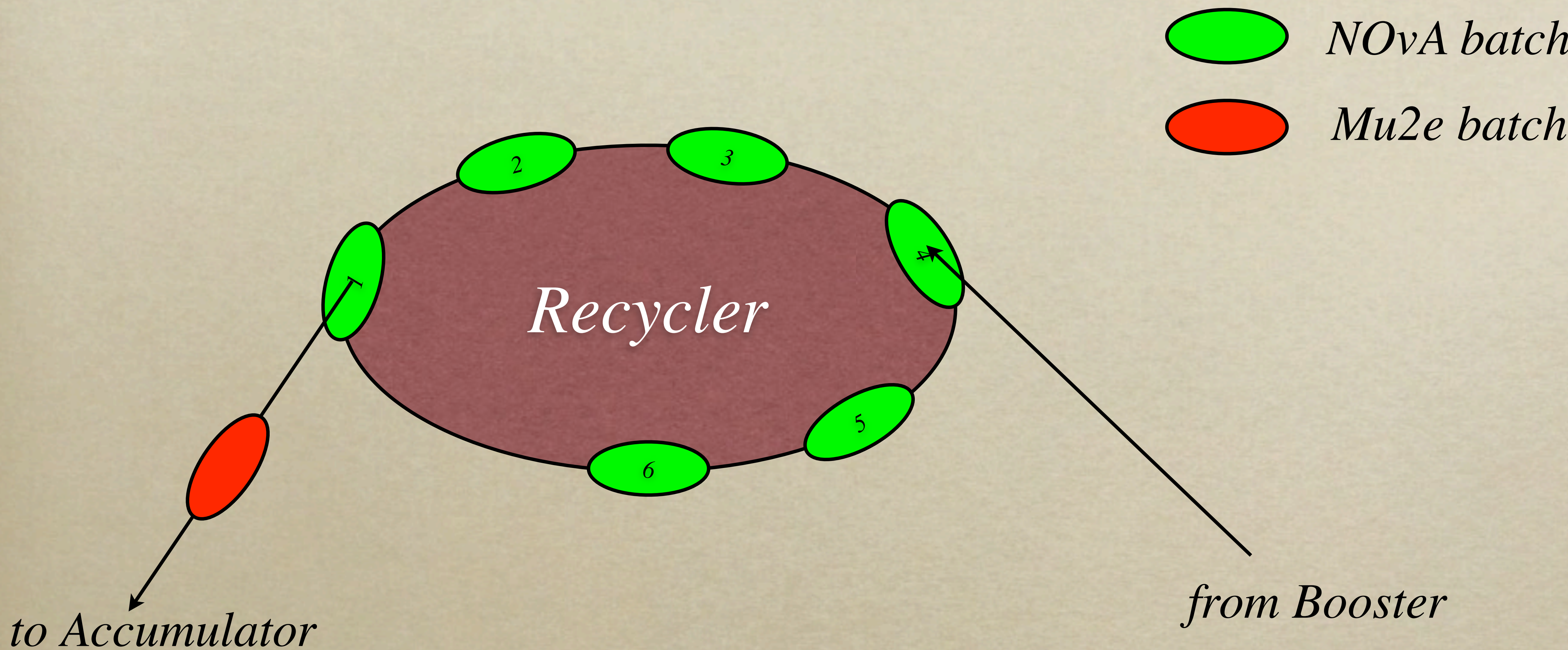
Threading Mu2e through NOvA



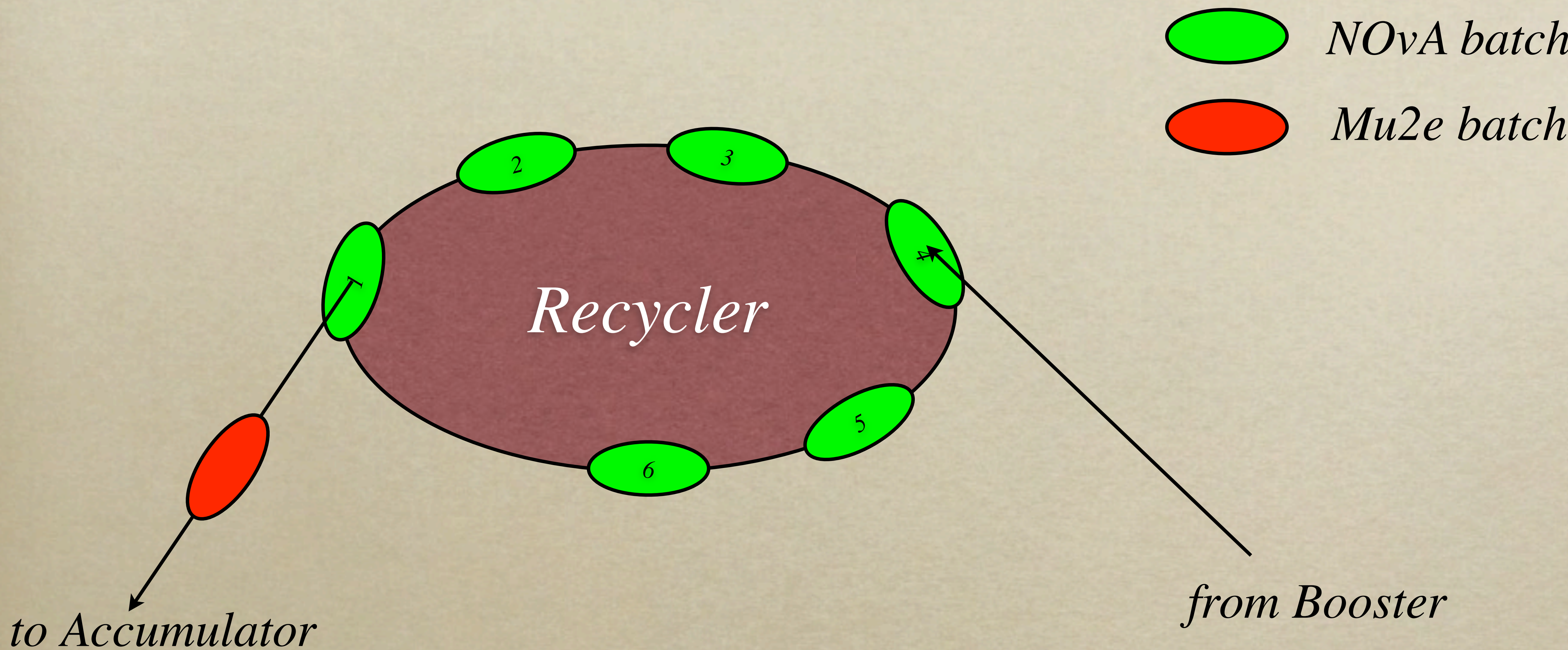
Threading Mu2e through NOvA



Threading Mu2e through NOvA

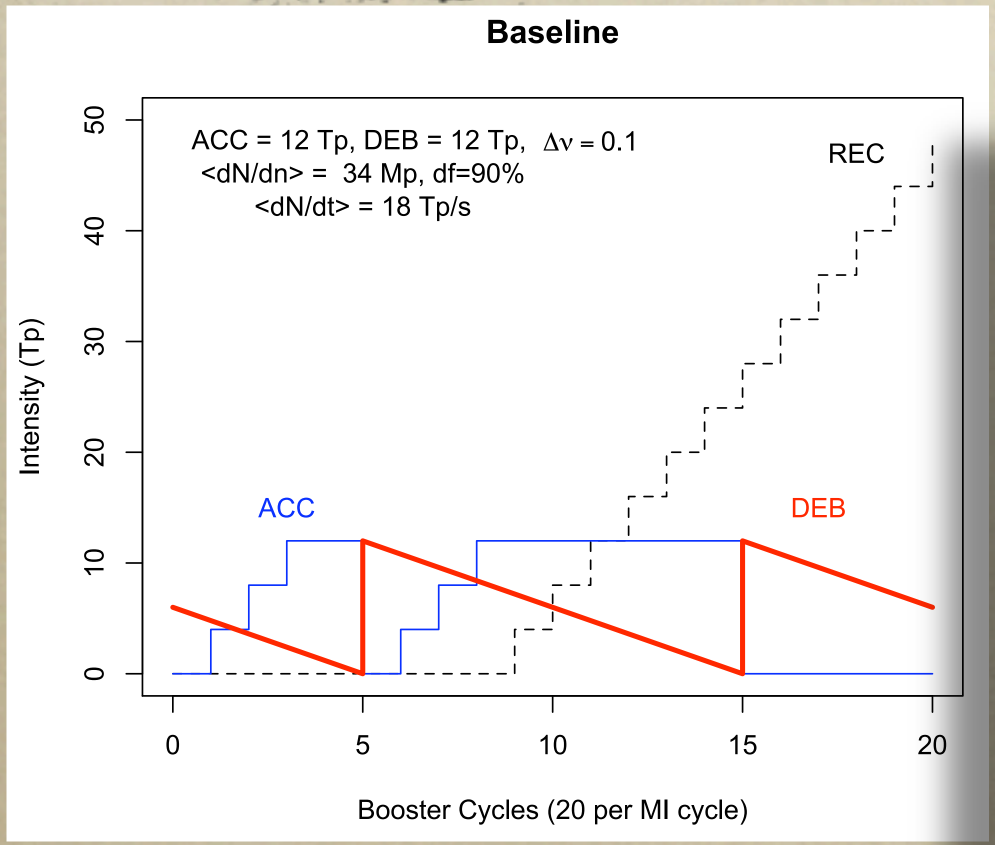


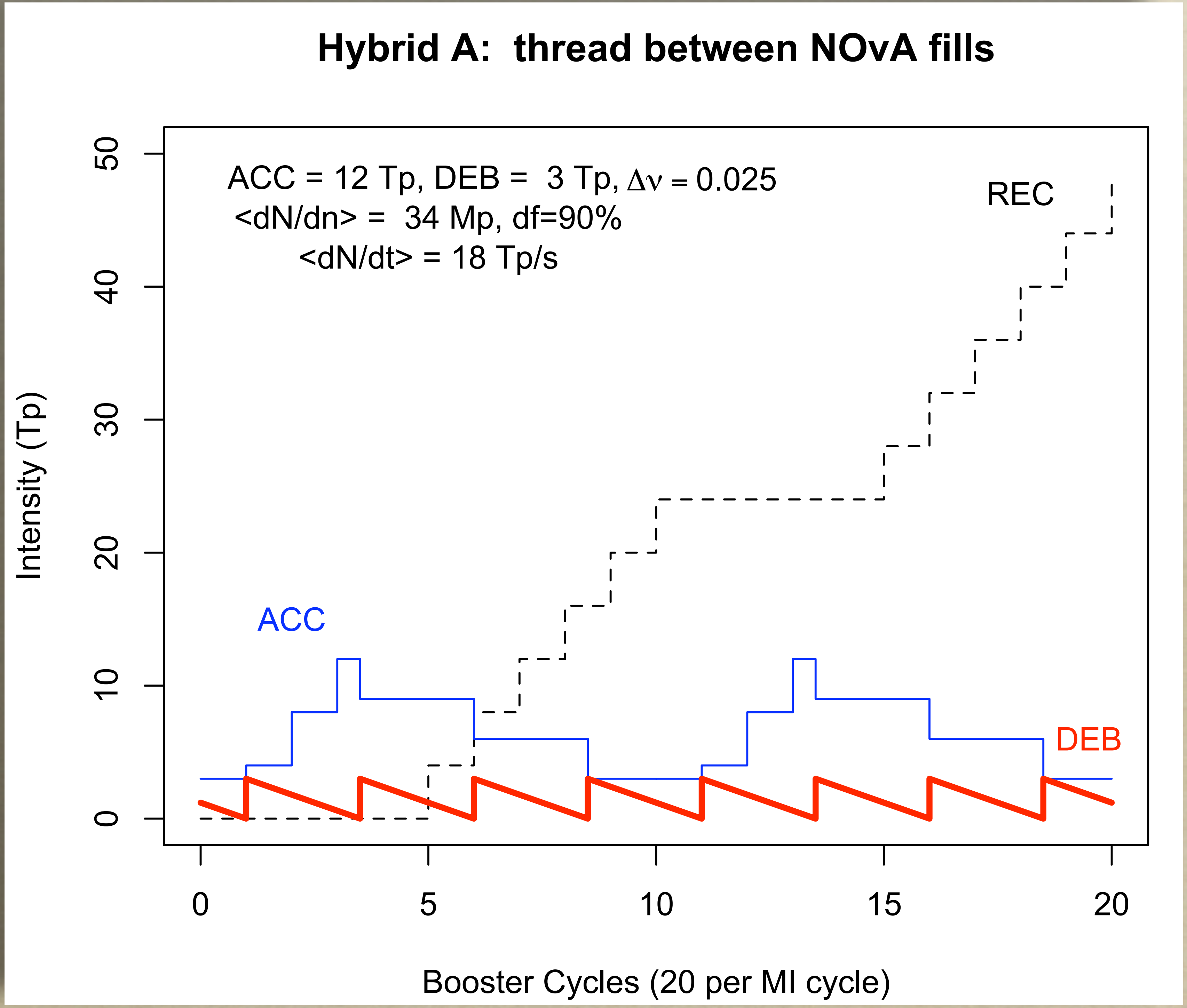
Threading Mu2e through NOvA



After final batches toward Mu2e have passed through, inject the last six batches for NOvA

Threading through NOvA





- *With threading, can split accumulated beam into 4 lower intensity bunches and transfer to the Debuncher one-at-a-time...*
- *Requires fast rise/fall-time Recycler extraction kickers, similar to injection kicker system*

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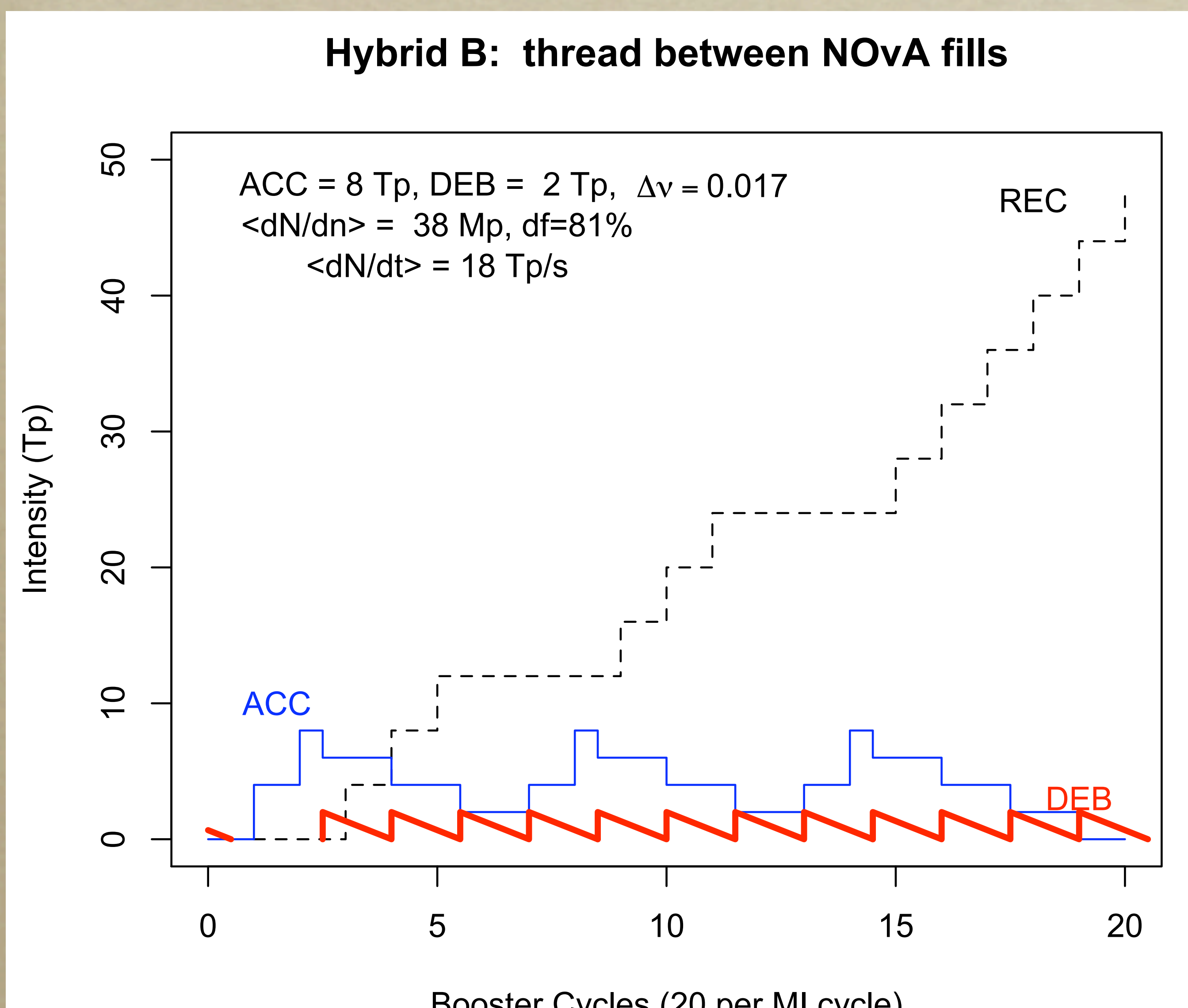
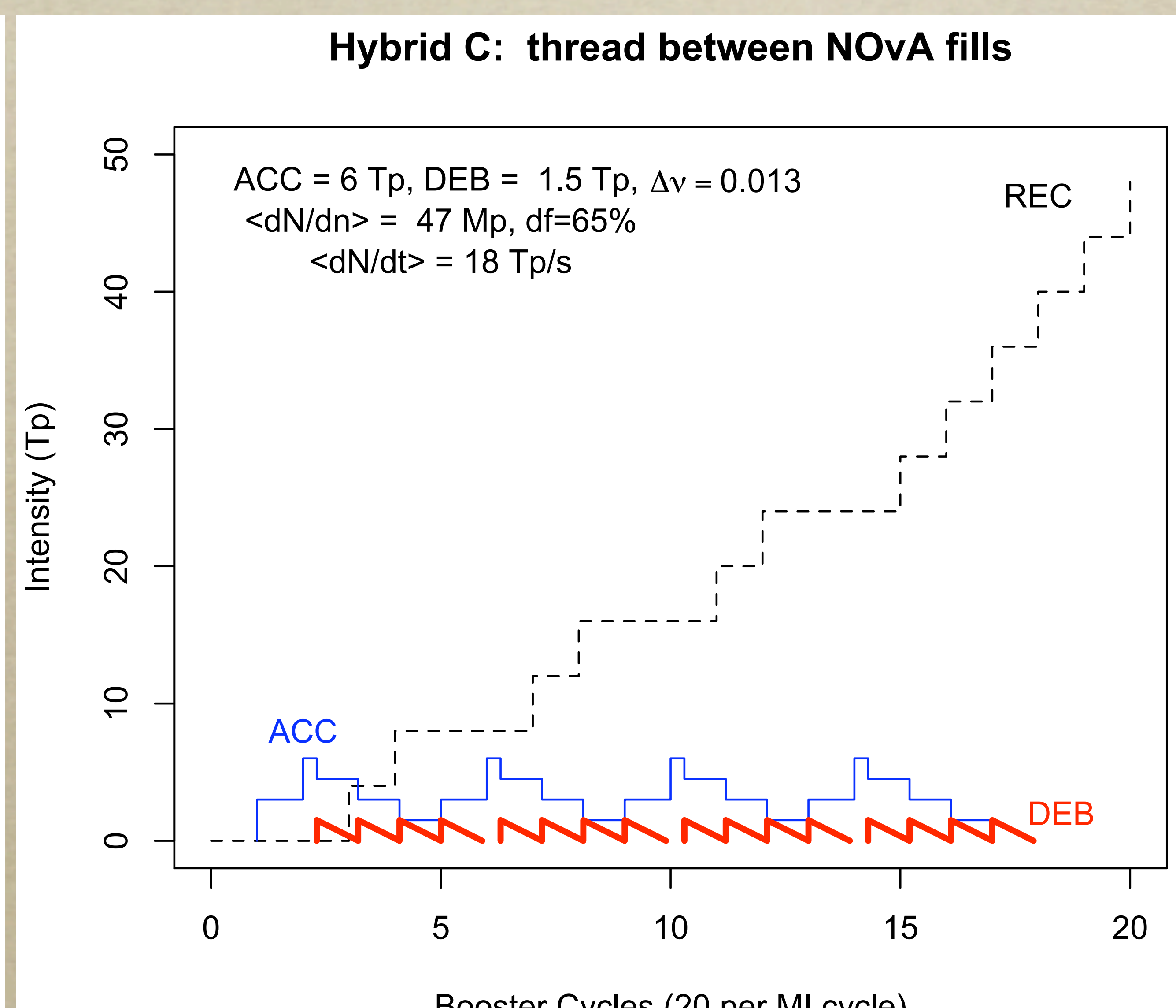
Threading through the Intensity Frontier

- *Also provides **flexibility** in operating scenario as learn to deal with high intensities, rates to the experiment, or other program planning issues along the way ... several variants are possible*





Comparisons

	Expt Cycle (BOO)	BOO pulses per Cycle	BOO intensity (Tp)	DEB intensity (Tp)	inst. <dp/dn> (Mp)	ave. <dp/dt> (Tp/s)	NOvA off <dp/dt> (Tp/s)	DEB sp. Chg. dnu
BASELINE	10	3	4	12	34	18	18	0.100
Full Rate (g-2) A	1	1	4	1	113	18	60	0.008
Full Rate (g-2) B	1	1	3	0.75	85	18	45	0.006
Hybrid A	10	3	4	3	34	18	18	0.025
Hybrid B	6	2	4	2	38	18	20	0.017
Hybrid C	4	2	3	1.5	47	18	22.5	0.013

- *Accumulator requires 53 MHz system for momentum stacking (as in Proposal) and a 2.4 MHz (h=4) system for bunch formation (625 kHz (h=1) in proposal).*
- *Debuncher requires h=4 system (**no** h=1).*
- *Bunch formation in Accumulator takes between 20-30 ms**

**See D. Neuffer, Fermilab-CONF-09-513-APC*

Compare Kicker Requirements

Mu2e Scenarios

	Expt Cycle (BOO)	Cycle time (ms)	Spills/Cycle	Cycles/MI	bunch form time (ms)	spill time (ms)	duty fact	NOvA Off duty fact
BASELINE	10	666.7	1	2	133.3	600	90%	90%
Full Rate (g-2) A	1	66.7	4	6	(REC)	15	27%	90%
Full Rate (g-2) B	1	66.7	4	8	(REC)	15	36%	90%
Hybrid A	10	666.7	4	2	33.3	150	90%	90%
Hybrid B	6	400.0	4	3	33.3	90	81%	90%
Hybrid C	4	266.7	4	4	20.0	54	65%	81%

Build to Hybrid B, can also work for A

TRANSFER KICKERS

	max rate (Hz)				*ave rate (Hz)*				*ave rate (Hz; NOvA off)*			
	REC out	ACC in	ACC out	DEB in	REC out	ACC in	ACC out	DEB in	REC out	ACC in	ACC out	DEB in
BASELINE	*dipole*	15	pulsed	pulsed	*n/a*	4.5	1.5	1.5	*n/a*	4.5	1.5	1.5
Full Rate (g-2) A	15	15	60	60	4.5	4.5	18	18	15	15	60	60
Full Rate (g-2) B	15	15	60	60	6	6	24	24	15	15	60	60
Hybrid A	15	15	6	6	4.5	4.5	6	6	4.5	4.5	6	6
Hybrid B	15	15	10	10	4.5	4.5	9	9	5	5	10	10
Hybrid C	15	15	16	16	6	6	12	12	7.5	7.5	15	15

Note: NOvA inj. kickers: 12/20x15 = 9 Hz (ave)
Booster ext. kickers: 15 Hz (ave)

Scenario Feasibility

- *Requires a "duplicate" set of kicker magnets in the extraction region as exists in the Recycler injection region required for NOvA*
  - *Baseline assumed a "pulsed dipole" for extraction*
- *Technique appears non-controversial to relevant AD specialists, NOvA project, etc.*
- *One less RF system (DEB) required*

Mu2e Extinction

- *Need extinction at level of 10^{-9}*
- *Internal -- what do we start with?*
    - *during bunch formation, how do particles get left behind?*
    - *after bunch formation, how do particles access the "gap"?*
- *External -- what is our last resort?*
    - *AC dipole system*

Internal Extinction

Let's assume some noise sources…

- *here,* $\Delta\phi_{rms} \sim 1^o$

  (for dramatization)

- 0.1^o *more typical*

- *utilize scrapers at high momentum dispersion locations to catch particles before they escape bucket…*

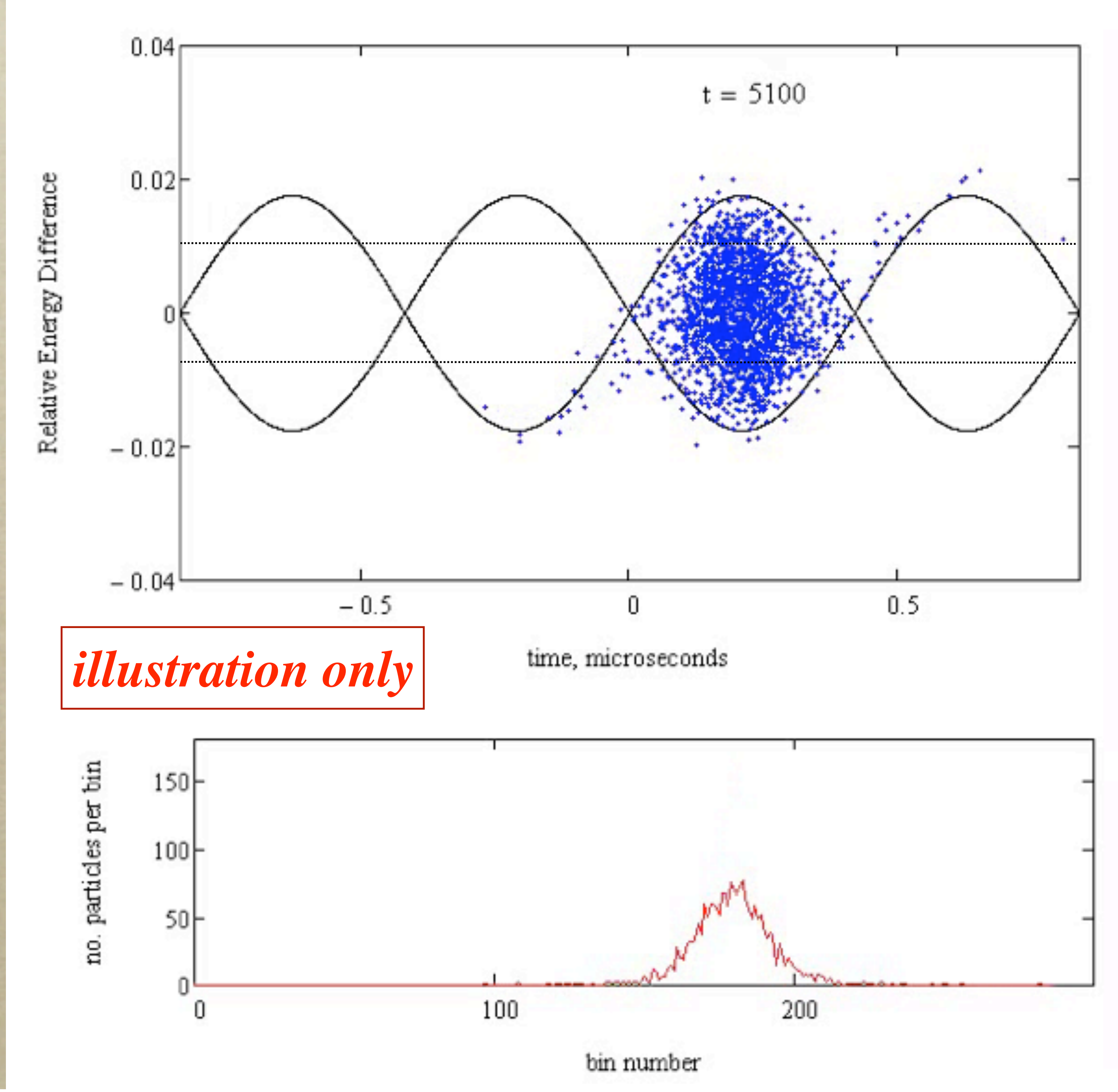


illustration only

Internal Extinction

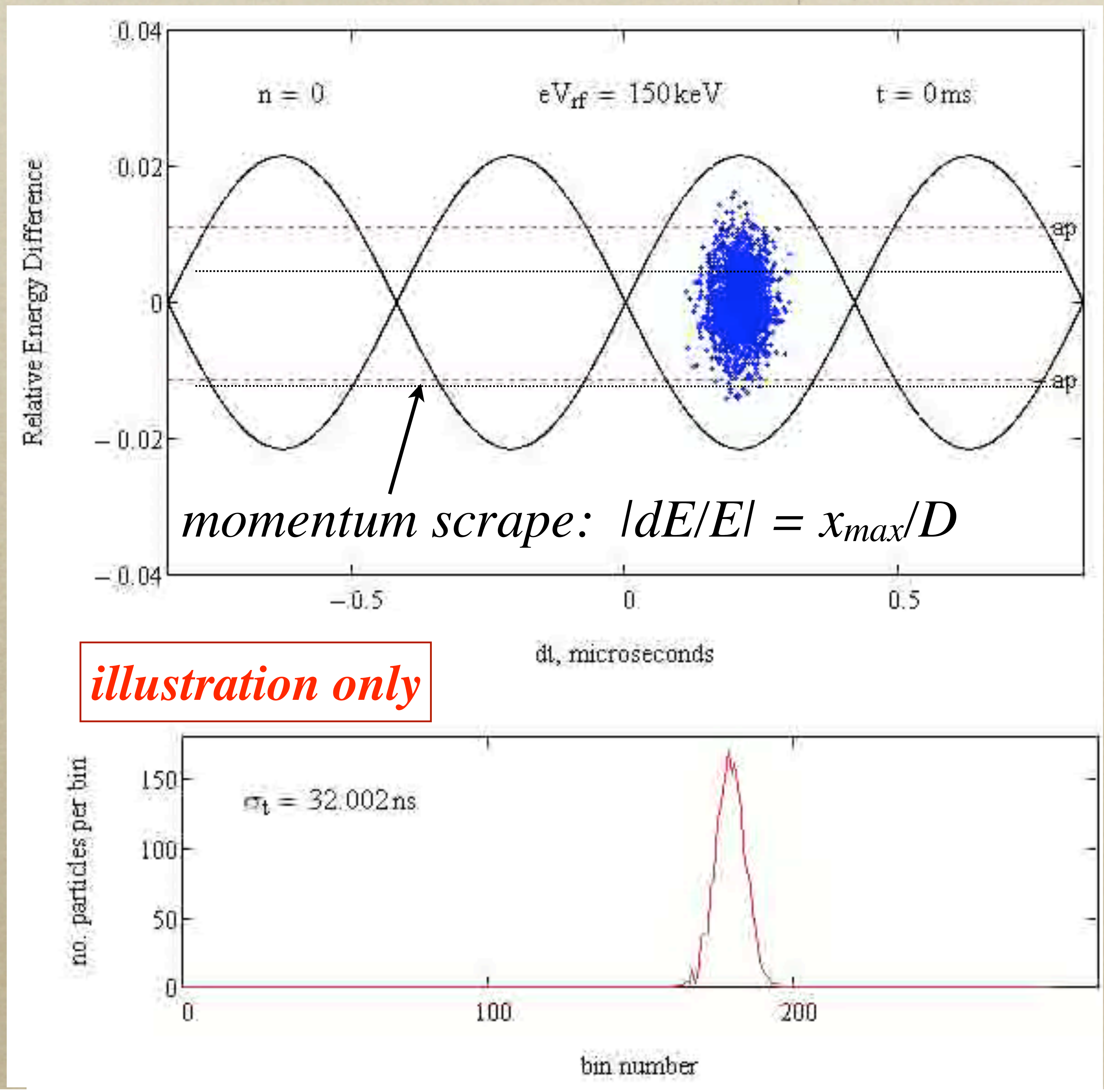
Let's assume some noise sources…

- *here, $\Delta\phi_{rms} \sim 1^o$*

  (for dramatization)

- *0.1^o more typical*

- *utilize scrapers at high momentum dispersion locations to catch particles before they escape bucket…*



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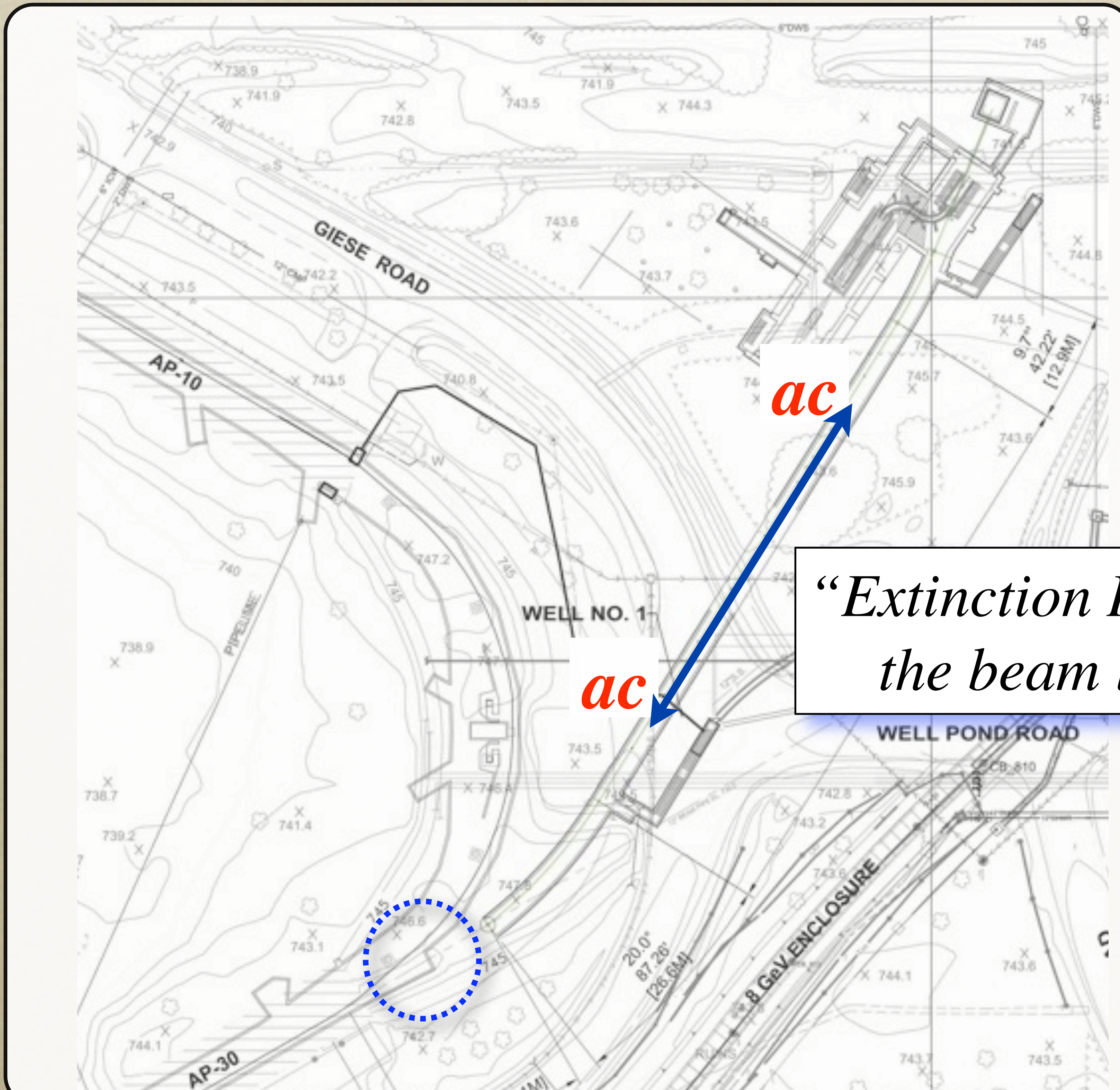
External Extinction

"Last Resort" for extinction adjustment



"Extinction Insert" within the beam line design

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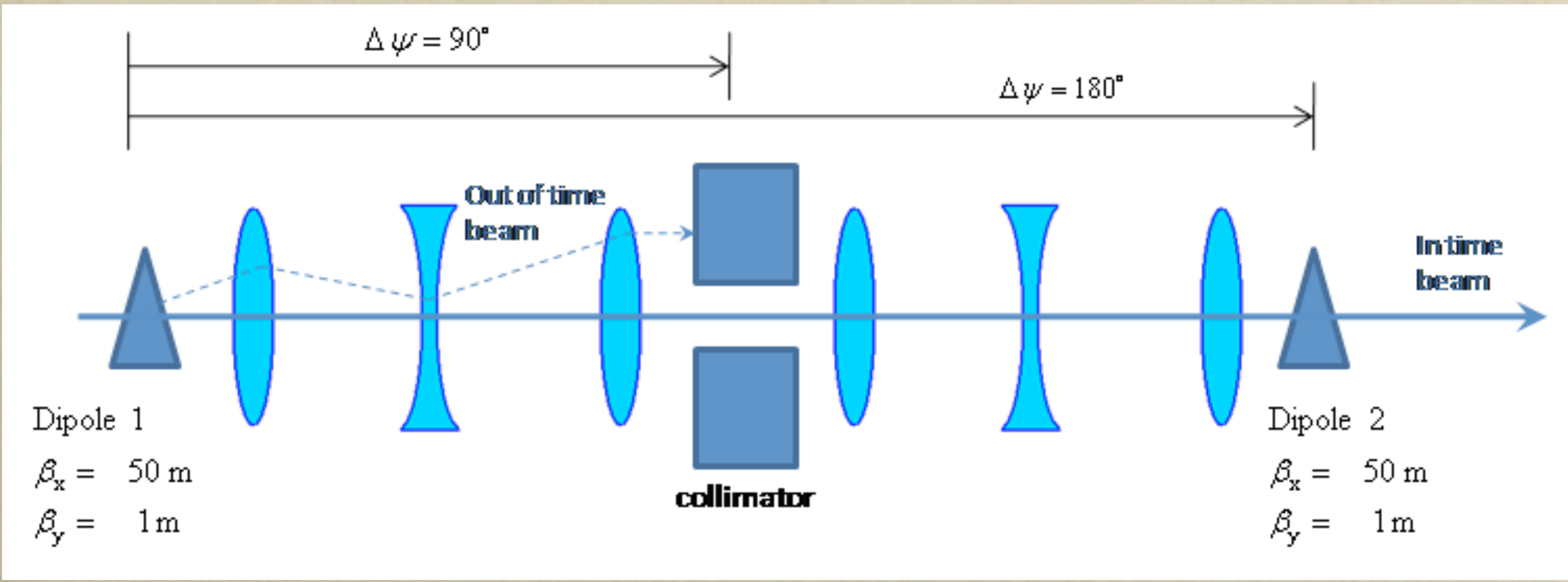
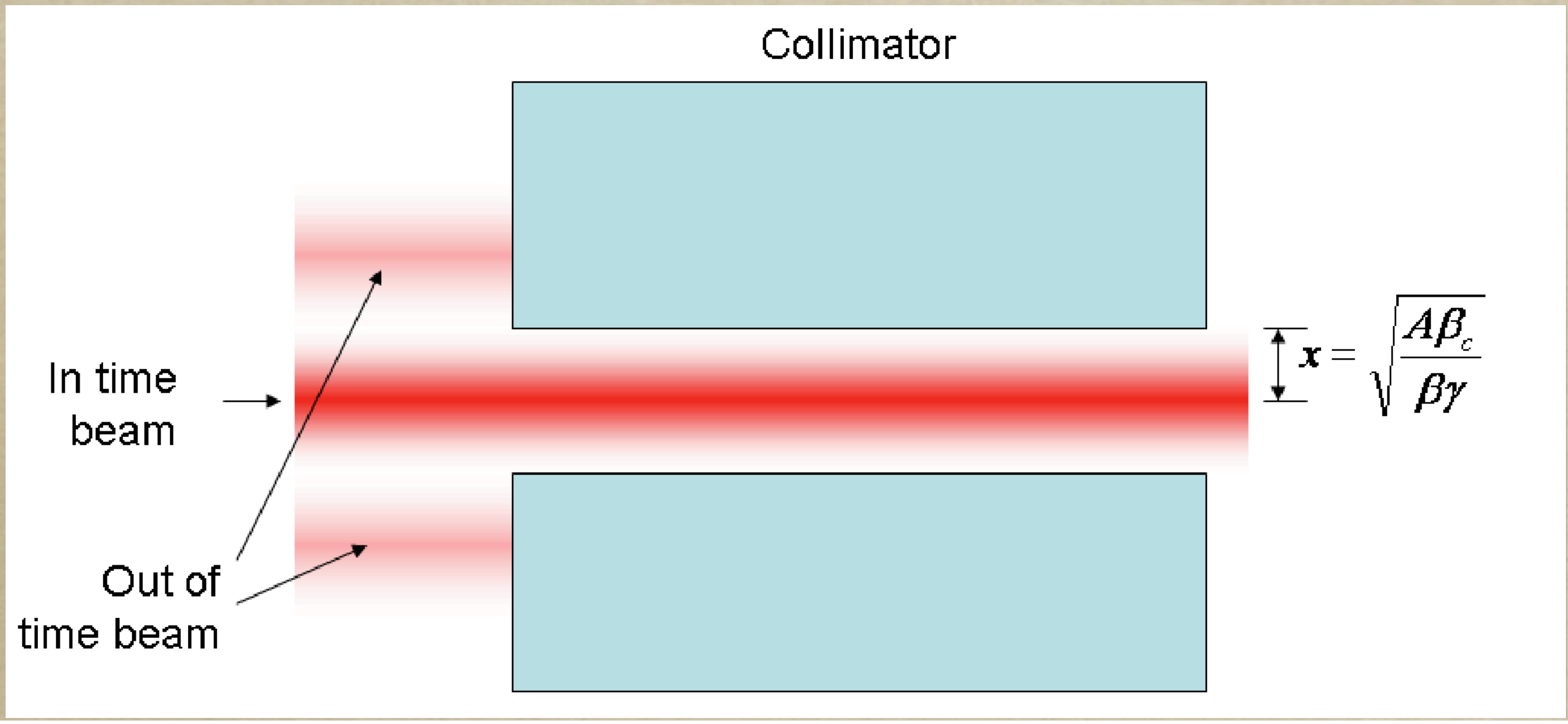
Extinction Insert Concept

(from the Proposal)



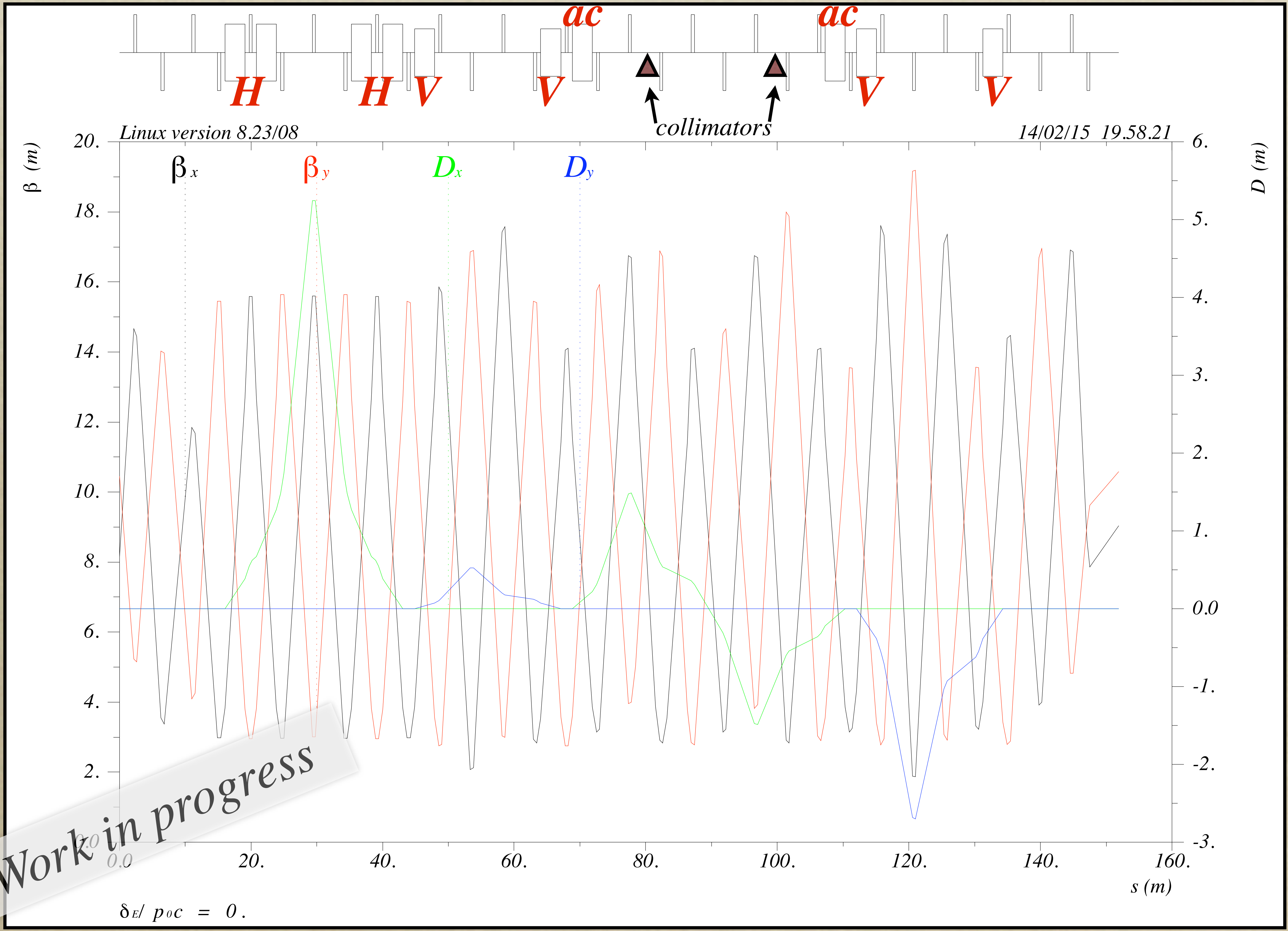
- *design insert as part of transport line between Debuncher and experiment*

- *"AC dipoles" kick out-of-synch particles into collimators*
- *Likely wish 2-stage collimator system*



Beam Line Optics (so far...)*

Here, ends before the final H bend, and still need the final focus onto the target; Also, will optimize extinction insert optics



*C. Johnstone

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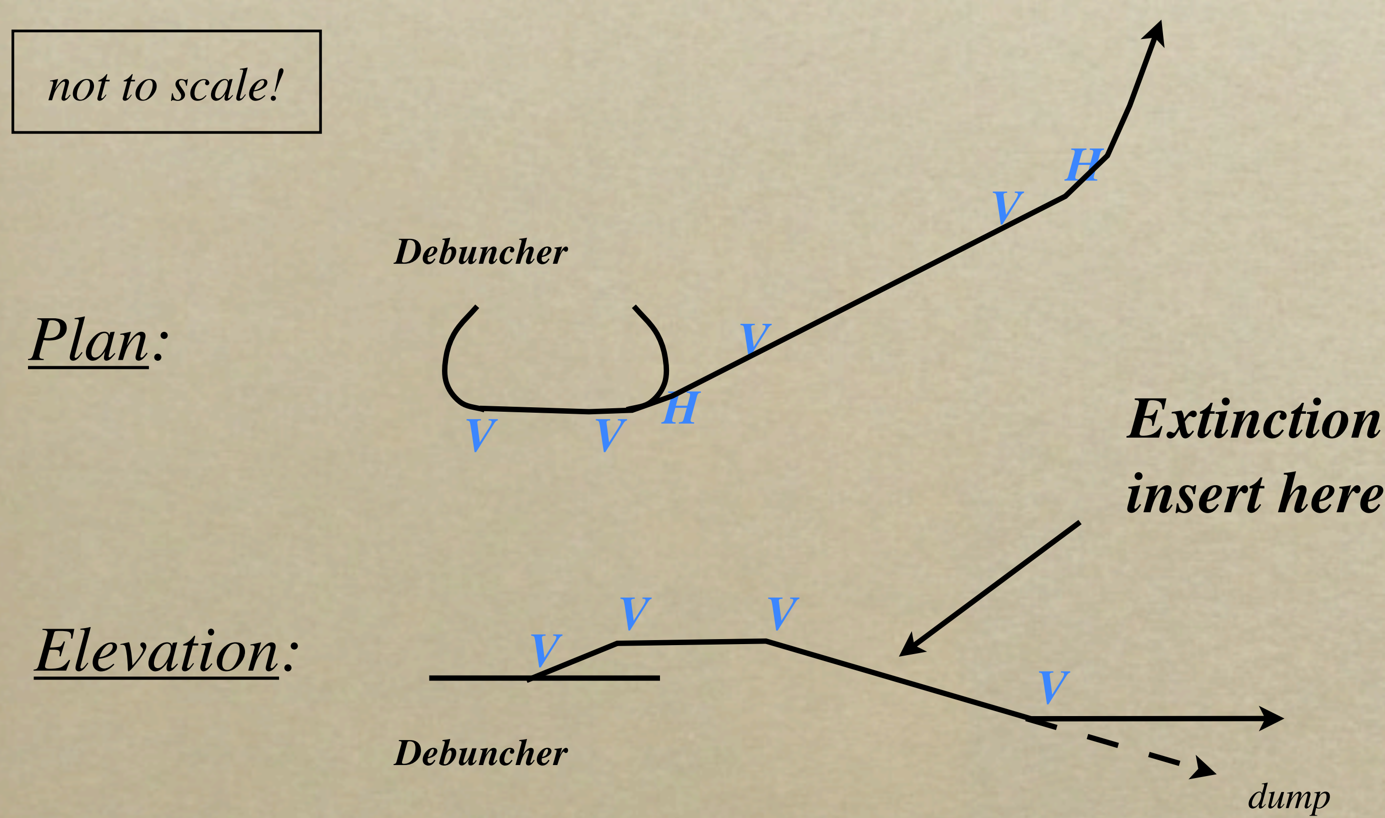
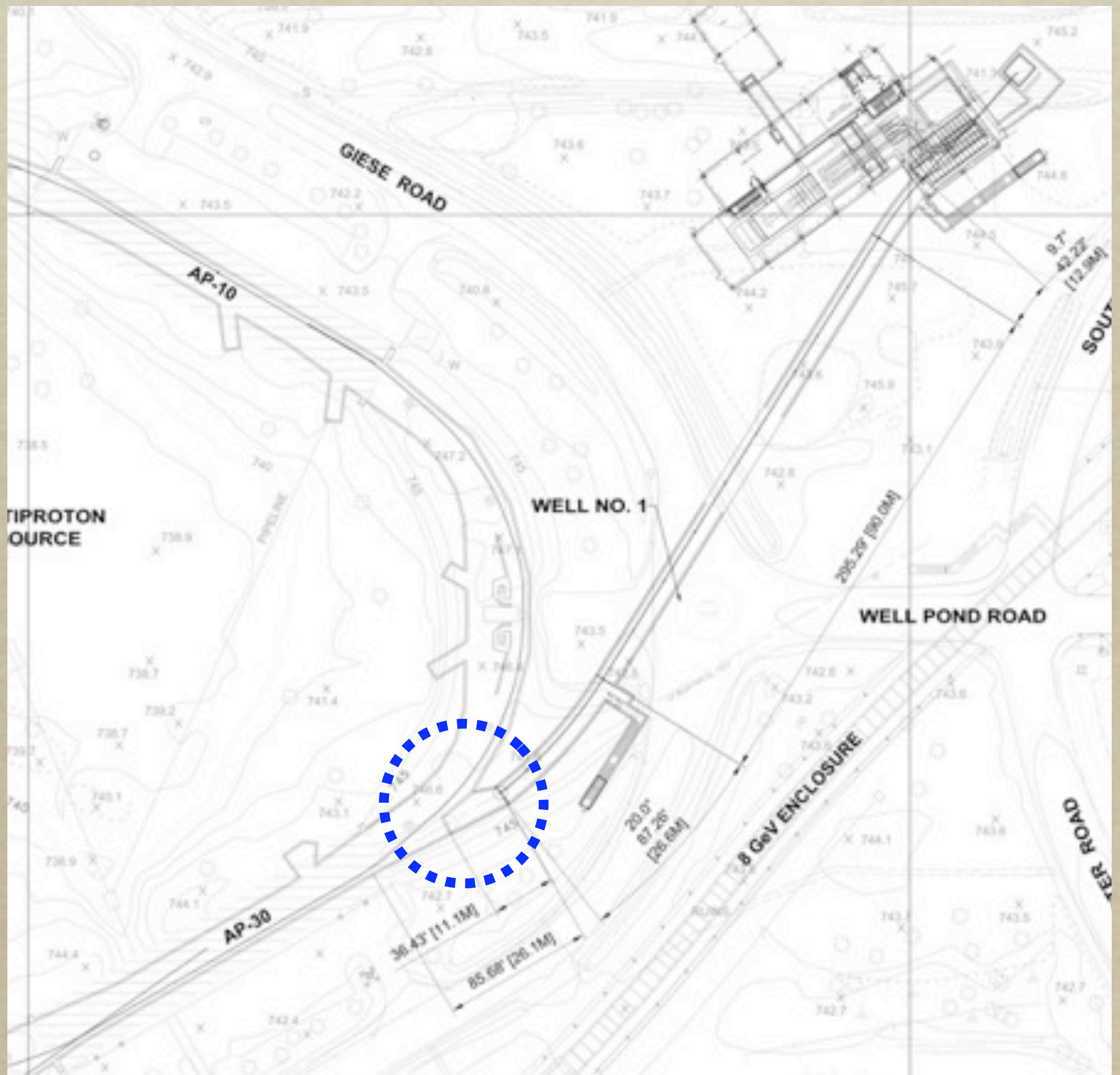
Mu2e Beam Line

- *Design work proceeding, utilizing existing "stub" in ring tunnel as the final exit point*



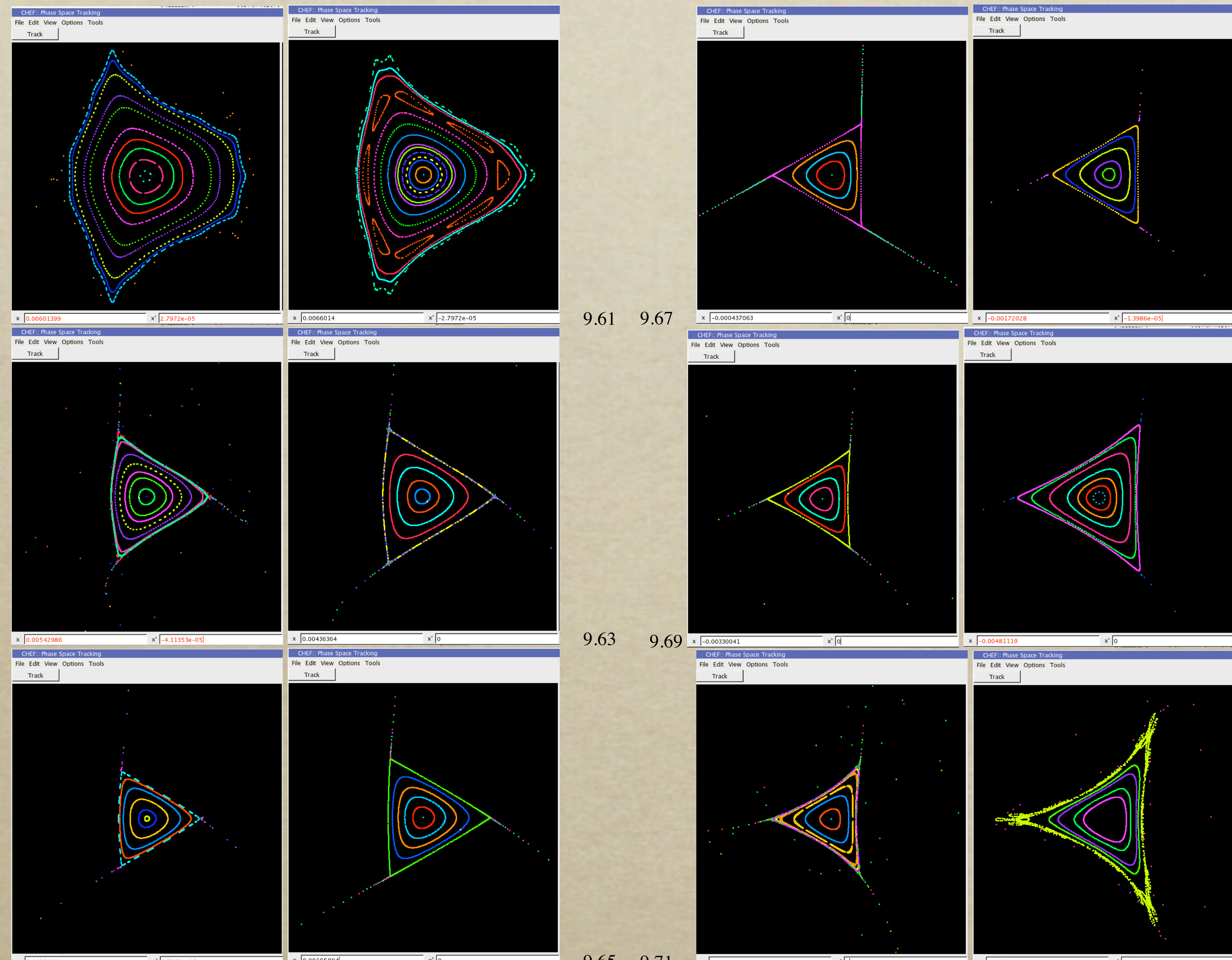


Work in progress

Exploration of Tune Space*

Tune space of Debuncher, near third-integer (tune ~ 29/3)

Need to control tune to within ~0.05 of resonance



9.60 9.61 9.67 9.68

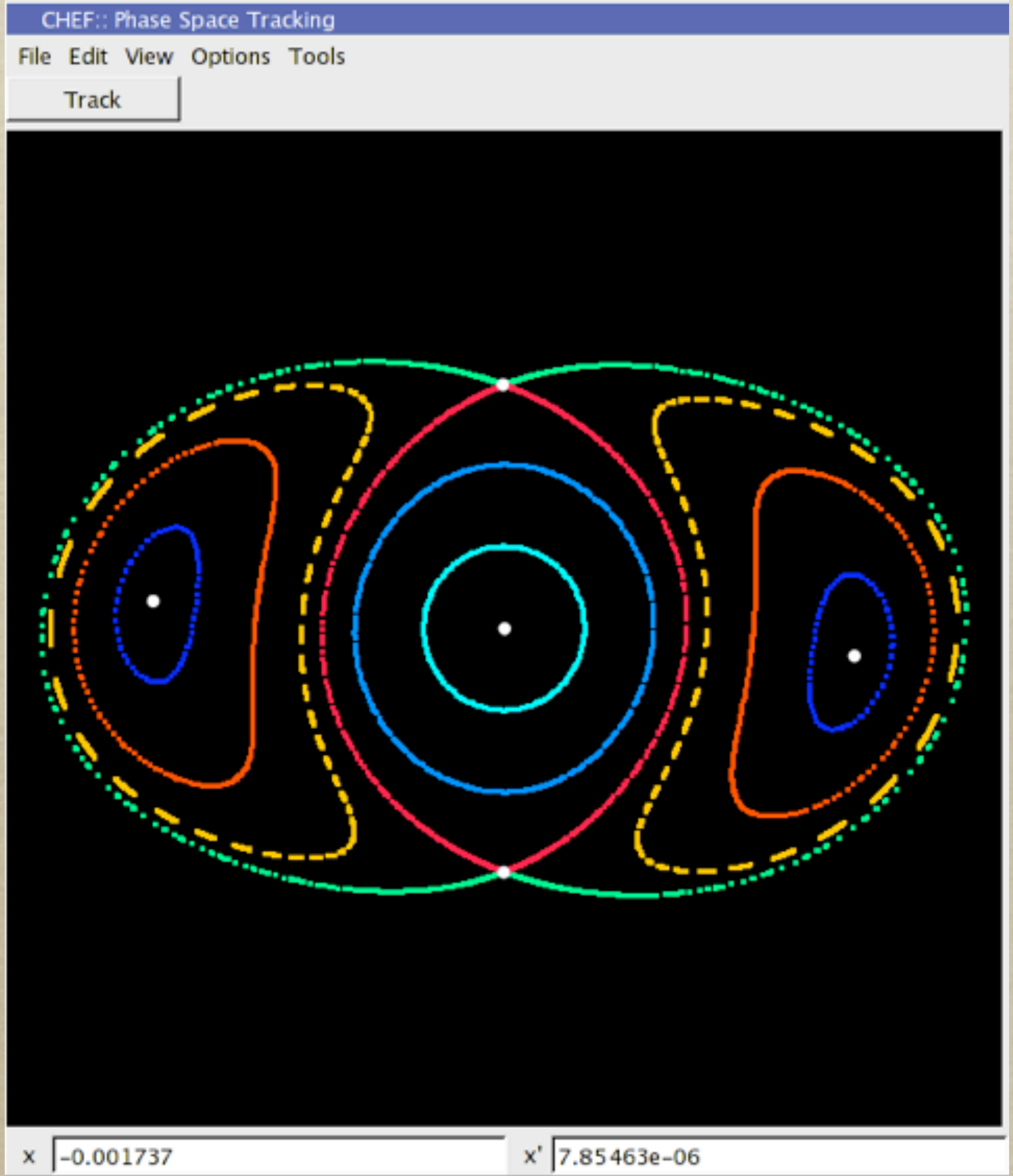
9.62 9.63 9.69 9.70

9.64 9.65 9.71 9.72

**Michelotti*

Half-integer Extraction

- *Work has begun to study half-integer extraction*
    - *phase space*
    - *corrector parameters*
- *Much experience at Fermilab -- MR, Tev, MI*
- *New technique is evolving which might deal with large tune distribution*



Michelotti

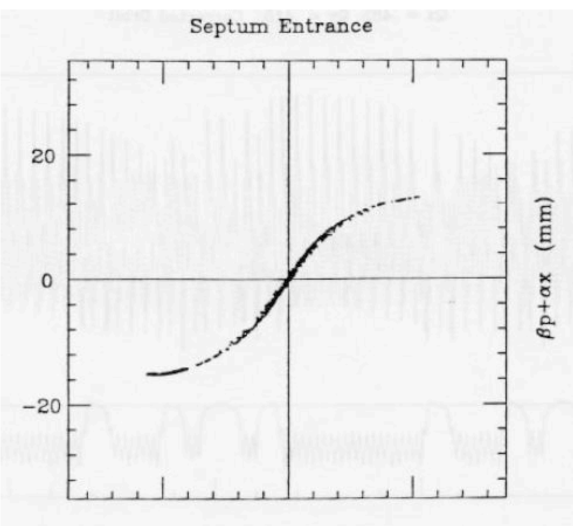
Historical Half-Integer Approach

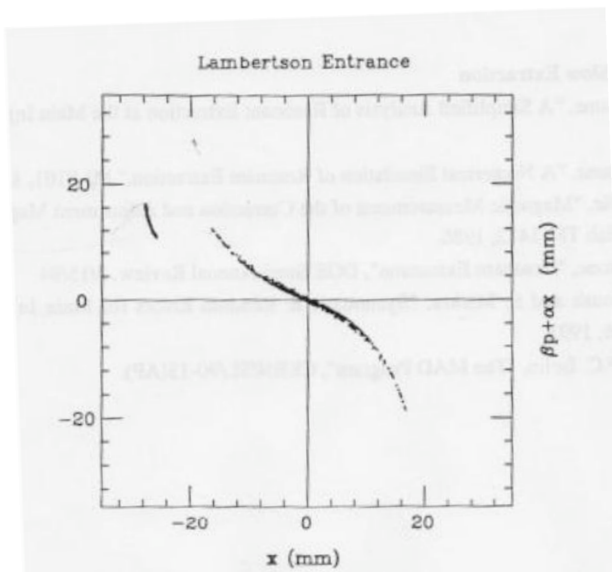
Resonant Extraction from the MI @ 120 GeV/c:

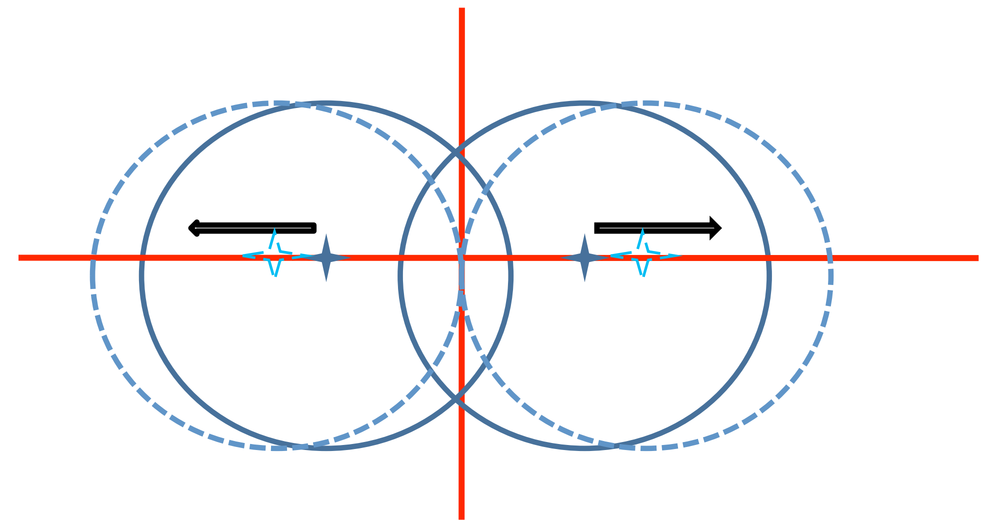
$Cx = +5$, & $\Delta p_{95}/p = \pm 0.04\%$:

Tune Spread $\Delta_{95} = 0.015 \pm 0.002$

$\Rightarrow$ ~12 mm *separation at Lambertson*







$$\left[x \pm \left(\frac{q_2\beta}{6\lambda}\right)^{1/2} \sin\left(\frac{\psi}{2}\right)\right]^2 + \left[x' \mp \left(\frac{q_2\beta}{6\lambda}\right)^{1/2} \cos\left(\frac{\psi}{2}\right)\right]^2 = \left(\frac{\Delta\beta}{6\lambda}\right)$$

Assuming a fixed circle radius the q_2 driving term is systematically increased to pull the circles apart, thereby decreasing the stable area to zero.

This approach to resonant extraction was used exclusively in the Main Ring, again in the Tevatron, and still today in the Main Injector.

- *J. Johnstone*
  - *see Mu2e-doc-576*

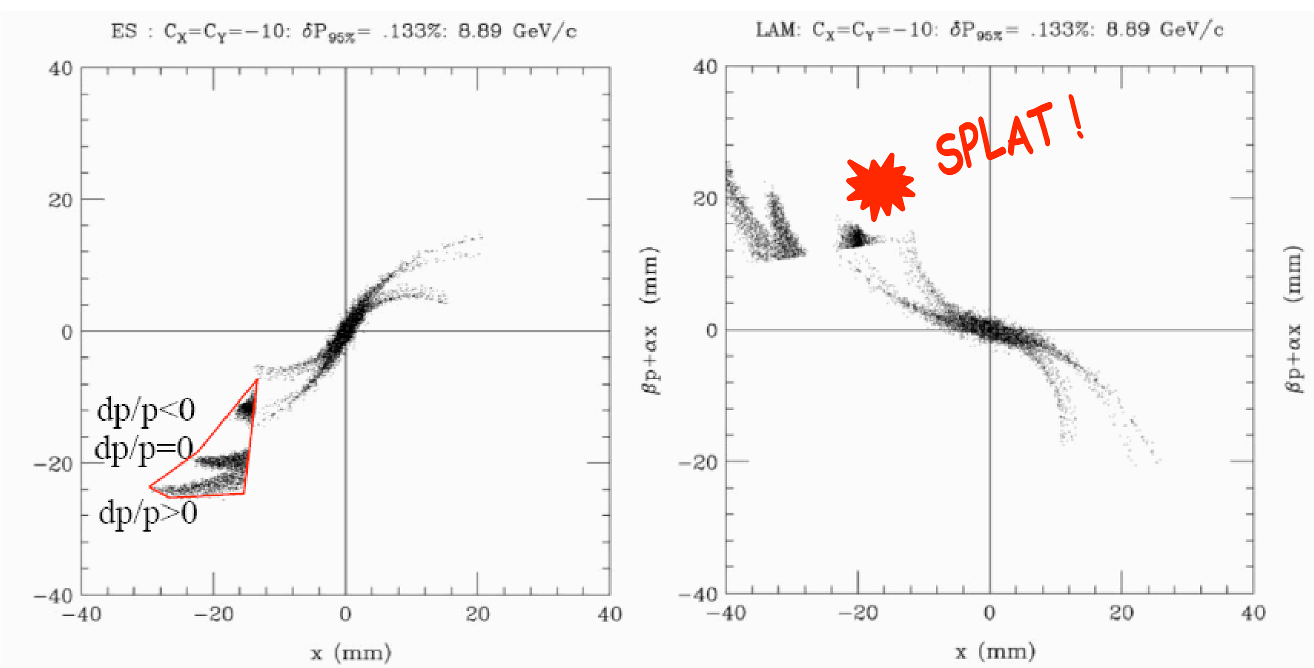
JJ’s Previous Study: Recycler

Simulated Extraction from the Recycler (actually MI) @ 8.9 GeV/c:

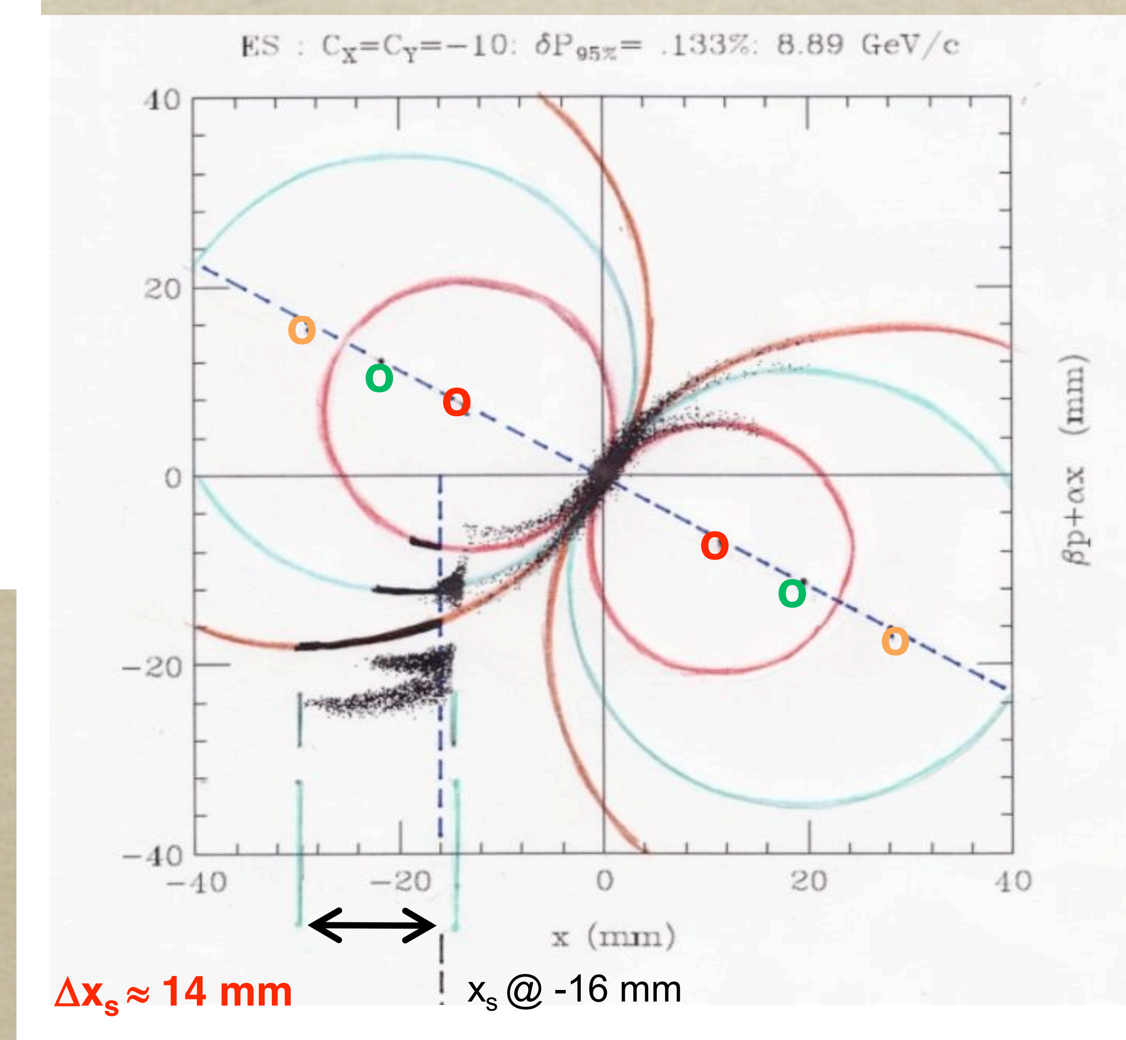
Cx = -10, & $\Delta p_{95}/p$ = ±0.133% :

Tune Spread Δ_{95} = 0.025 ± 0.0133

⇒ ***ZERO*** *separation at Lambertson !*



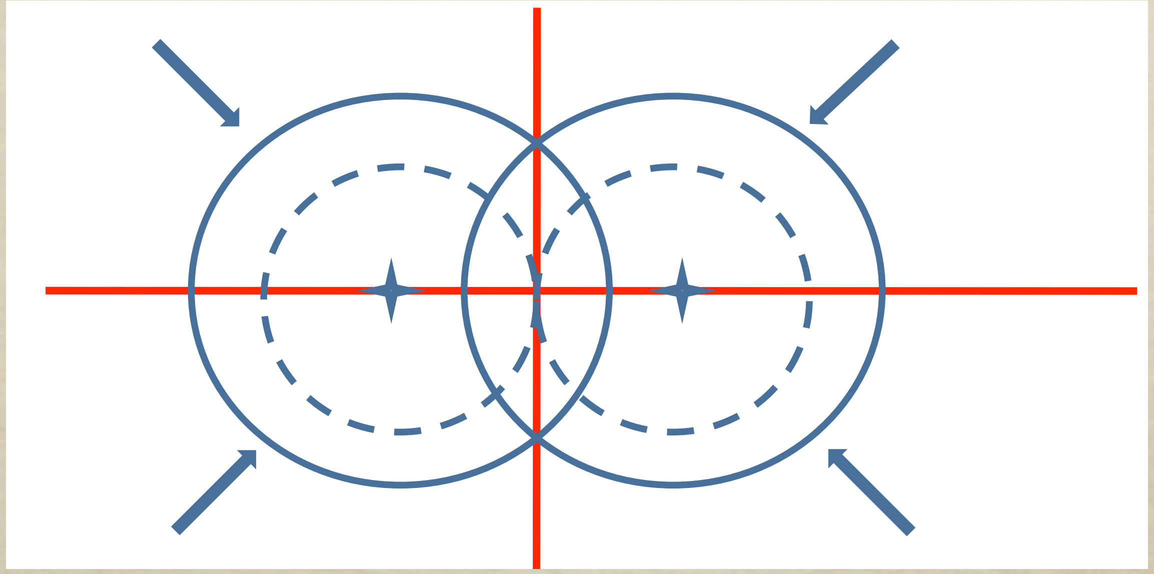
Different “circles” for different momenta (different tunes)



- *Large tune spread seemed problematic…*

New Idea

- *Instead, use a zeroth-harmonic quad circuit to vary the radius of circles, rather than pulling them apart...*



$\because \Delta = \Delta_{|initial} \rightarrow q_2$ covers the total extraction of emittance ε, irrespective of $\Delta p/p$:

- variation of the separatrices' circle radii are identical over the course of extraction;
- step-size at the septum is identical for all $\Delta p/p$, and;
- Extracted beam phase-space trajectories are identical for the entire range of $\Delta p/p$.

Looks promising; will want to try out in MI...

Summary

- The addition of a q_0 tune circuit has potential for greatly improving half-integer extraction in the event of a large tune spread.
- Because of the great similarity between the MI and Recycler lattices this technique can be tested in MI – the MI has all the necessary components already installed.

Ω

Extraction Studies

- *Several "teams" are looking at extraction*
  - *Johnstone, Michelotti (as noted above)*
  - *Nagaitsev, Werkema, Nagaslaev -- simple model, but with a space charge code (ORBIT, from ORNL)*
  - *Amundson, Spentzouris -- full 3-D space charge simulations*
- *Will look for opportunity, following the start-up, to test out this new process in the MI*

RF Knock-Out?

- *In the Medical industry, beam therapy has stringent requirements on spill lengths and uniformity*
- *Many systems now control slow spill by using RF transverse-mode cavities to gently kick the beam toward a separatrix*
  - *investigating possibility for use in Mu2e*

8 GeV Summary

- *Mu2e is approved experiment, and will face several challenges*
  - *bunch formation and manipulations*
  - *high intensity, space charge; frequent slow spills*
  - *high level of extinction -- produce and monitor*
  - *25 kW production targeting in solenoid field*
  - *new level of particle throughput in the existing "pbar" rings -- radiation safety issue*

8 GeV Summary

- *New g-2 Experiment is seeking approval; challenges will include*
  - *moving of existing ring from BNL*
  - *bunch formation and manipulations*
  - *25 kW production targeting in AP0*
    - *80 kW for pbars, but pulse rate, stresses, etc., much different*
  - *reconfiguration of AP2/3 for pion capture, muon decay*

8 GeV Upgrade Program -- AIP's?

- *Mu2e and g-2 share several line items*
- *Their components could also be used for other programs as well*

Example:

targeting R&D could be carried out using AP0 target hall in support of many FT programs (8 GeV and other)

Contents of a possible 8 GeV MEDIUM ENERGY FIXED TARGET upgrade project

program: *targeted proton momentum:*	NOvA *120 GeV/c*	microBooNE *8.9 GeV/c*	**g-2** *8.9 GeV/c*	targetry R&D *8.9 GeV/c*	EDM *8.9 GeV/c*	**Mu2e** *8.9 GeV/c*	*muCool R&D* *8.9 GeV/c*	kaons, other *8.9 GeV/c*
Upgrades for Mu2e, g-2								
Proton Source (*off-project*)								
Boo RF upgrades (cones, etc.) for 15 Hz		√	√	√	√	√	√	√
Boo solid state upgrade, for reliability	√	√	√	√	√	√	√	√
Preac upgrade (RFQ); reliability, hi curr	√	√	√	√	√	√	√	√
Recycler								
injection system from MI8 line	√		√	√	√	√	√	√
pbar decommissioning	√		√	√	√	√	√	√
extraction system to P1 line			√	√	√	√	√	√
2.5 / 5.0 MHz / brdbnd RF systems			√	√	√			
Beam Transport Lines								
AP2 optics improvements			√		√			
AP3 optics improvements			√		√	√	√	√
AP0 Targeting System								
target station			√	√	√		√?	
beam collection system			√	√	√		√?	
Synchrotrons (*prev. known as pbar rings*)								
rad safety improvements			√		√	√	√	√
pbar decommissioning			√		√	√	√	√
injection / extraction kicker systems			√		√	√	√	√
instrumentation upgrades			√		√	√	√	√
2.4 / 2.5 MHz RF systems						√	√	√
resonant extraction system						√	√	√
Muon Ring								
Muon Ring Building			√		√			
Muon Ring			√		√			
Beam transport from AP3 Line			√		√			
New Extracted Beam Line								
beam transport						√	√	√
collimation system						√	√	√
extinction system						√		
beam line dump						√	√	√
instrumentation system(s)						√	√	√
target system						√	√	√

draft examples...

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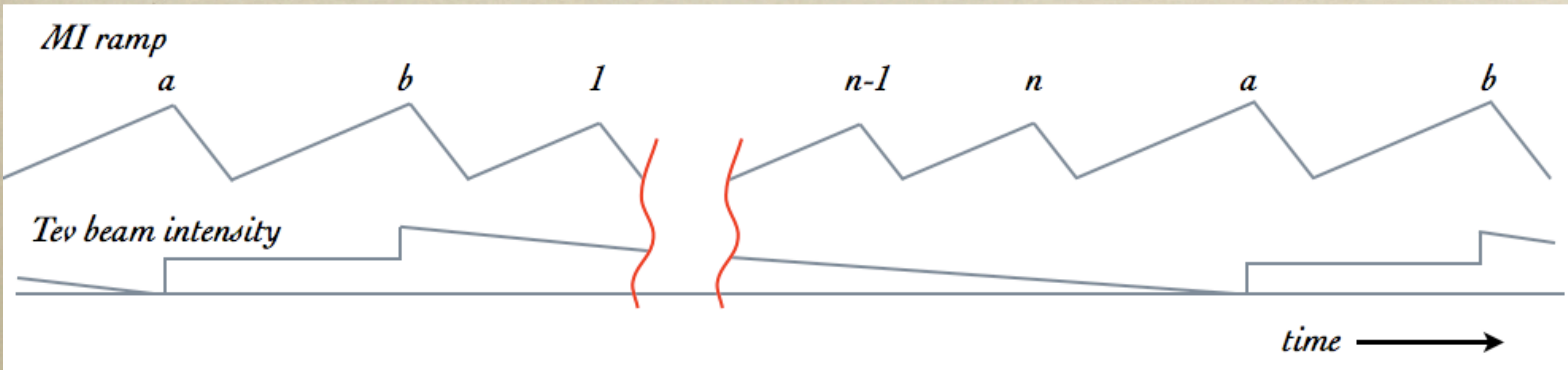
The Tevatron Stretcher

- *With the Tevatron Collider Run II complete, the possibility will exist to use the Tevatron as a "stretcher" ring to provide high intensity, high duty factor beams to fixed target experiments*
    - *SY120/150 -- the existing SY120 program could be fed from the Tev, perhaps upgraded to 150 GeV*
    - *Kaons Redux -- Proposal P996 has been submitted for $K^+ \to \pi^+ \nu \nu_{bar}$ search using Stretcher concept*

Tevatron Stretcher

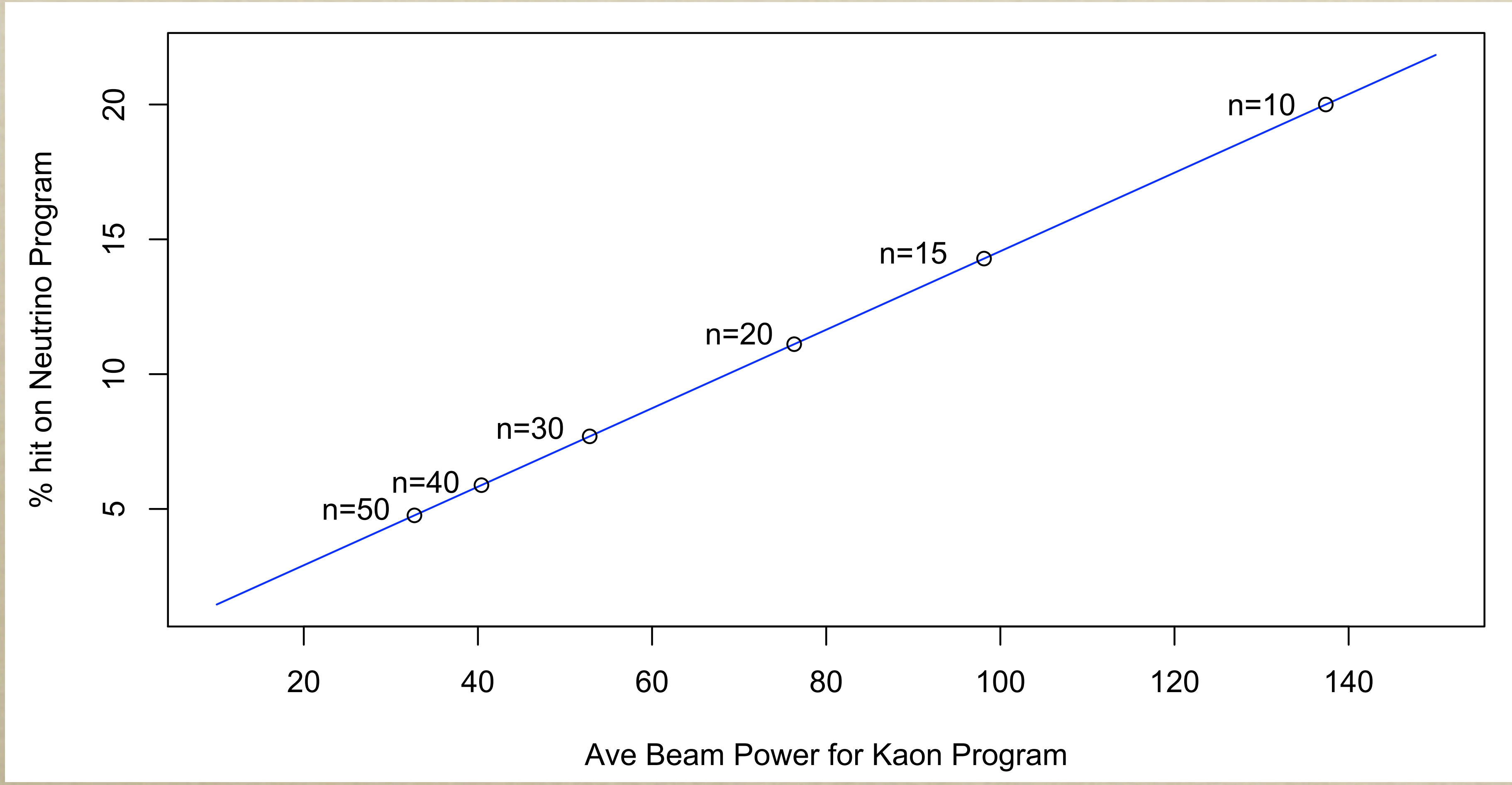


- *Take two MI pulses to fill the Tevatron, followed by n pulses to NOvA*
- *Slow spill over the n+1 MI cycles to fixed target experiments from the Tevatron*
- *If can accept two full MI beam fills, potentially 80-100 x 10^{12} (100 Tp) into the Tevatron at 150 GeV*

Current record ~30 Tp, due to:

high-energy instabilities,
and
Main RING

NOvA Impact

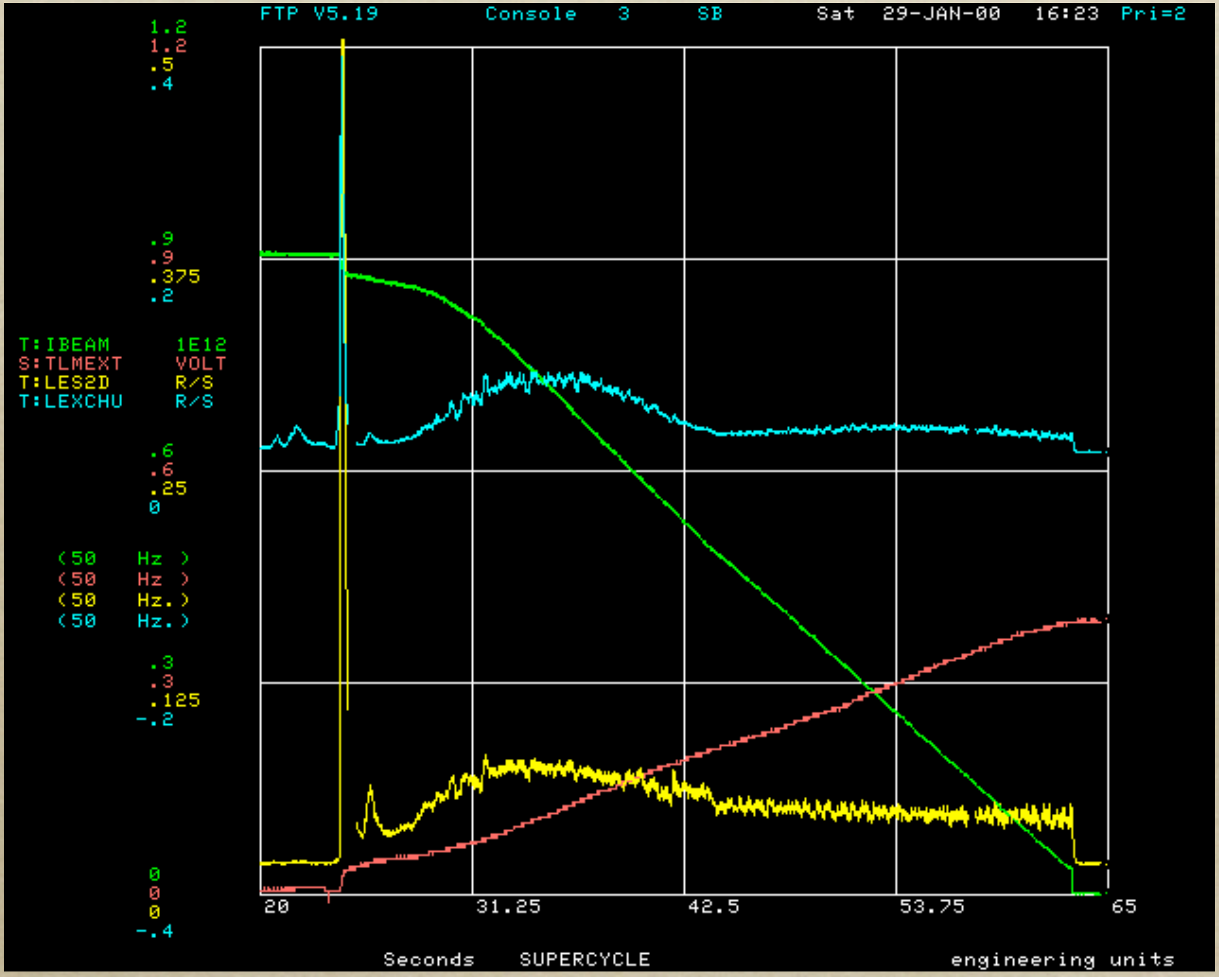


- *Can have respectable, high duty factor beam with ~10% hit to NOvA*
- *Can use to feed MTest as well, with no further impact on NOvA*

T_0[s]	df[%]	hit[%]	P_{ave}[kW]	P_{max}[kW]	$\dot{N}_{max}$[Tp/s]
16.67	90	20	137	153	6
23.33	93	14	98	106	4
30.00	94	11	76	81	3
43.33	96	8	53	55	2
56.67	97	6	40	42	2
70.00	98	5	33	34	1

Has Been Demonstrated

- *Well, sort of ...*
- *KAMI had a short run at the end of the final Tevatron Fixed Target run -- the last beam resonantly extracted from the Tevatron! (Jan 2000)*
- *Performed at 150 GeV with very low intensity*
  - *(~1 Tp/spill over 30 s)*



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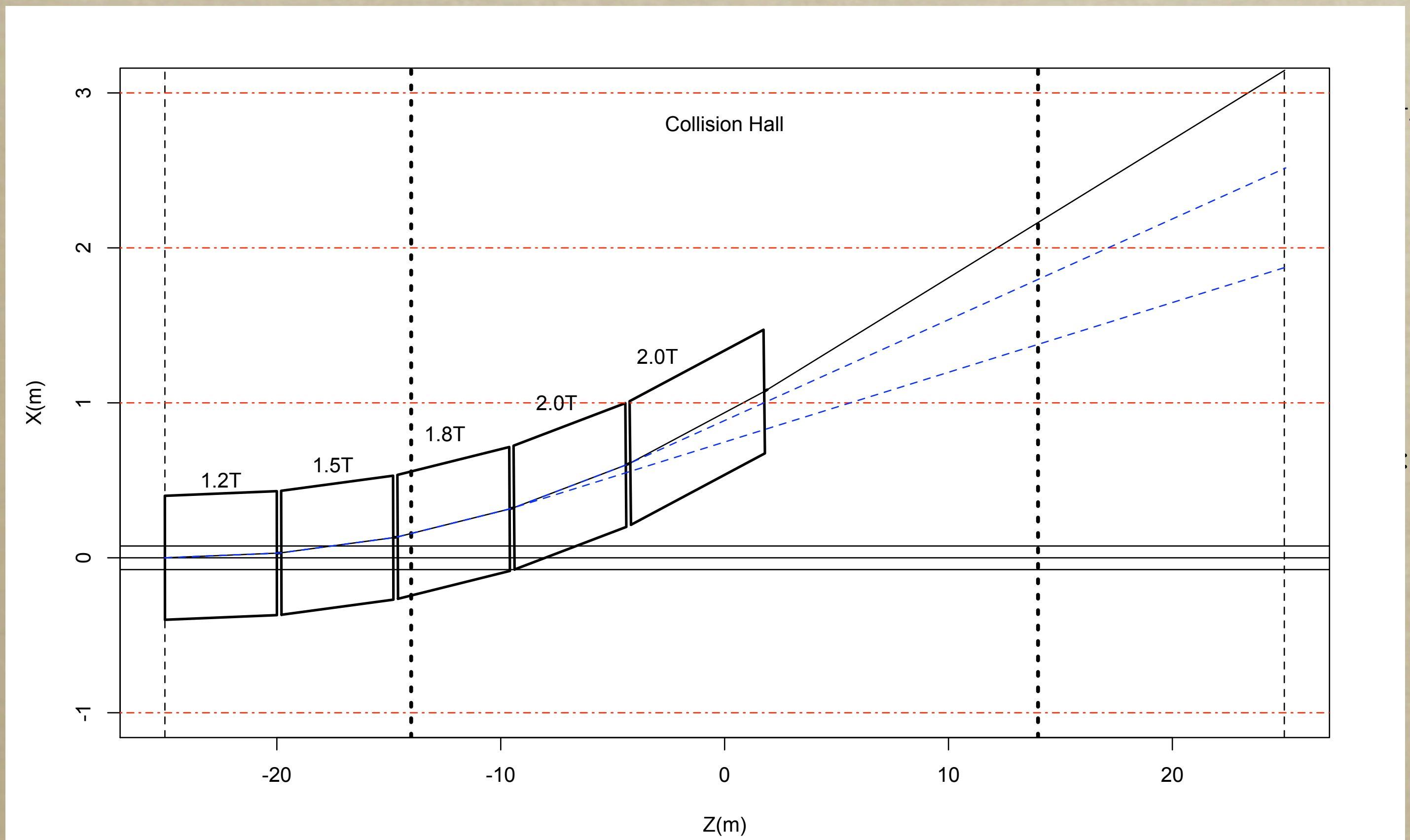
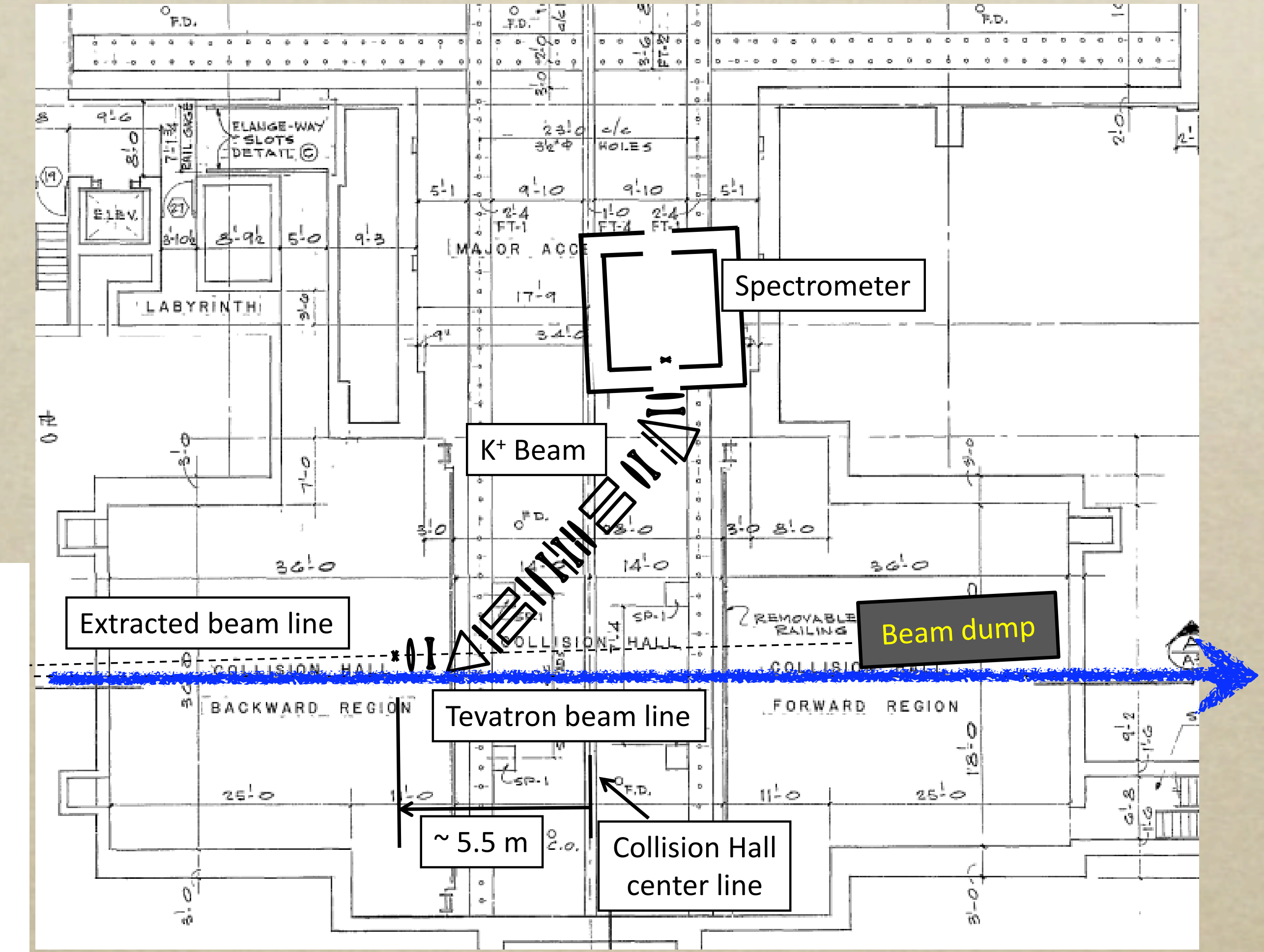
Tev150 Program

- *With one proposal on the dockets, use of the Tevatron as a Stretcher allows for a fixed target program to develop*
  - *Kaon experiment proposed (P996)*
  - *MTest in operation @ 120 GeV; modify line to 150 GeV*
  - *Opens avenue to future experiments in SY, or in Tev*
- *Kaon proposes using CDF/B0; can explore either...*
  - *multiple extraction points from Tevatron, or*
  - *pulse separate extraction devices, orbit bumps during spill*

Kaon Experiment at B0

- *Would perform 1/2-int. resonant extraction (vertically) into horizontally bending Lambertson magnets and C-magnets*
- *Well-shielded beam dump in Collision Hall forward region; experiment "fits" within CDF Hall and access area*





: Illustration of the P996 beamline and detector sited within the B0 collision hall.

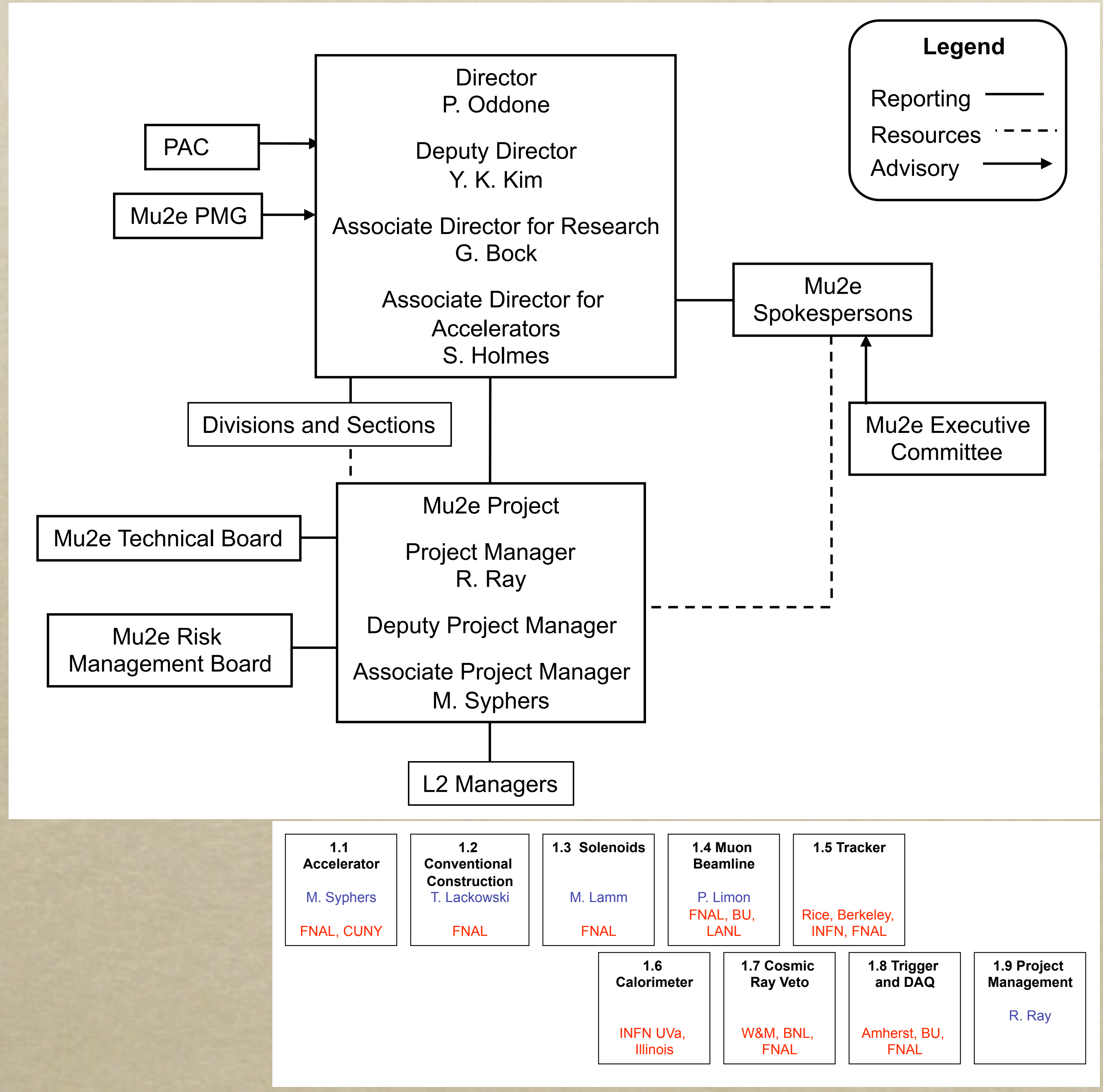
(from P996 Proposal)

Status of Programs

- *Mu2e moving forward*
  - *Efforts are being "project"-ized with CD-0 now in hand, working toward CD-1 in about 12-15 months*
- *New g-2 efforts have included cost scrubbing and further development of targeting plan, ring relocation and re-assembly, building plan, etc.*
- *Stretcher concept should be fairly "straightforward" to implement -- return Tevatron to Fixed Target mode -- though will take much careful planning and effort*

Accel L2 Management for Mu2e

- *Balancing act:*
  - *costs, schedule, space charge effects, use of Recycler (or not), g-2?, NOvA on/off, time line flexibility, ease of operation, ...*
- *Developing requirements*
- *Generating WBS*
- *Mapping out R&D plan*



Beam Requirements -- Mu2e

- *Generating list of 'requirements'*
- *Receiving further input from collaboration*
- *Mu2e-doc-585*

Mu2e Accelerator and Beams
Identifcation of Requirements

Definitions:

bunch == group of particles circulating in accelerator
microbunch == group of particles arriving to Mu2e
distributions assume Gaussian, unless noted

Strawman *list of possible parameters:*

Time between microbunches	1685 ns	(fixed)
Transmission Window (centered on microbunch center)	200 ns	
Transmission Window jitter	2 ns	
Extinction Level		
Measurement window:	900 ns	
A = no. particles to target during measurement window		
B = no. particles to target during transmission window		
X =A/B		
Maximum allowed X =	1.00E-07	Is there
Desired X =	1.00E-09	a "max"?
(need specification of an "extinction function" (of time)?)		
Maximum integrated intensity per microbunch on target	70 Mp	
Desired integrated intensity per microbunch on target	35 Mp	
Maximum Time Average dN/dt on target	25 Tp/s	
Desired Time Average dN/dt on target	18 Tp/s	
Minimum Time Average dN/dt on target	10 Tp/s	
(averaged over many seconds)		
Maximum rms transverse spot size on target	3 mm	
Desired rms transverse spot size on target	1 mm	
Minimum rms transverse spot size on target	0.25 mm	
(above assumed to be "round")		
Maximum transverse beam divergence on target	0.3 mr	any req?
Maximum length of slow spill period	600 ms	
Minimum length of slow spill period	50 ms	
Minimum duty factor	75 %	
Maximum rms microbunch length on target	50 ns	(assumed
Desired rms microbunch length on target	30 ns	Gaussian)
Minimum rms microbunch length on target	20 ns	
Maximum rms energy spread of beam on target (+/-)	100 MeV	
corresponding dE/E_max =	1.12 %	
Desired rms energy spread of beam on target	50 MeV	
corresponding dE/E_rms =	0.56 %	

Mu2e Accelerator Systems -- WBS

- *Work Breakdown Structure has been drafted*
- *Some detail down to "Levels 5, 6"*
  - *WBS Dictionary being developed to define terms*

```
WBS Item
1.1 Mu2e Accelerator
    1.1.1 Proton Source
        1.1.1.1 15 Hz RF upgrade
    1.1.2 Recycler
        1.1.2.1 Recycler R&D
        1.1.2.2 Injection System
        1.1.2.3 RF Systems
        1.1.2.4 Instrumentation
        1.1.2.5 Cooling Removal
        1.1.2.6 Extraction System
    1.1.3 Accumulator Ring
        1.1.3.1 Accumulator R&D
        1.1.3.2 Injection System
        1.1.3.3 RF Systems
        1.1.3.4 Instrumentation
        1.1.3.5 Cooling Removal
        1.1.3.6 Extraction system
    1.1.4 Debuncher Ring
        1.1.4.1 Debuncher R&D
        1.1.4.2 Injection System
        1.1.4.3 RF Systems
        1.1.4.4 Instrumentation
        1.1.4.5 Cooling Removal
    1.1.5 Radiation Safety Improvements
        1.1.5.1 Rad Safety R&D
        1.1.5.2 REC-ACC Beam Line Upgrade
        1.1.5.3 ACC/DEB Tunnel/Buildings
          Upgrade
    1.1.6 Resonant Extraction System
        1.1.6.1 Resonant Extraction R&D
        1.1.6.2 Electrostatic septa
        1.1.6.3 Magnetic septa
        1.1.6.4 Fast Trim Magnets
        1.1.6.5 Fast Feedback Magnets
        1.1.6.6 Cabling
        1.1.6.7 Installation
        1.1.6.8 Fast Feedback Electronics
    1.1.7 External Beam Line
        1.1.7.1 Beam Line R&D
        1.1.7.2 Beam Transport
        1.1.7.3 Beam Line Dump
        1.1.7.4 Safety System
    1.1.8 Extinction
        1.1.8.1 Extinction R&D
        1.1.8.2 Internal Extinction System
        1.1.8.3 External Extinction System
    1.1.9 Target Station
        1.1.9.1 Targeting R&D
        1.1.9.2 Target
        1.1.9.3 Target Handling
        1.1.9.4 Sheilding
        1.1.9.5 Cooling
        1.1.9.6 Instrumentation
    1.1.10 Accelerator Controls Software
    1.1.11 Management and Documentation
```

Mu2e Accelerator R&D

- *Might see opportunities arise for beam studies over the next year*
- *Designs, studies will continue, leading to a Design Document*
- *Engineering effort needs to build up for critical systems*

- *Beam --*
  - *Bunch formation techniques (MI)*
  - *Stopband measurements (DEB)*
  - *Bunch capture in ring (ACC)*
  - *Extinction measurement (ACC)*
  - *Slow spill technique (MI)*
- *Paper --*
  - *Scenario Development (Mu2e)*
  - *MI8/REC transfer design (AD/MI)*
  - *Radiation Safety (AD/AS)*
  - *Bunch formation systems (AD/RF)*
  - *Beam Line design (AD/EB)*
  - *Extinction design (APC)*
  - *Target design (AD/EB)*
- *Engineering --*
  - *AC dipole development (TD; AD/EE)*
  - *Kicker R&D (AD/EE)*
  - *RF systems design (AD/RF)*
  - *DEB fast corrector development (TD; AD/EE)*

Mu2e Weekly Accelerator Meetings

- *Weekly meetings have been held, involving personnel from Particle Physics, Accelerator, Technical, Computing Divisions and Accelerator Physics Center*
- *typically ~10-20 in attendance*

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* Total number of users subscribed to the list: 58
* Total number of local host users on the list: 0
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Accel L2 for New g-2

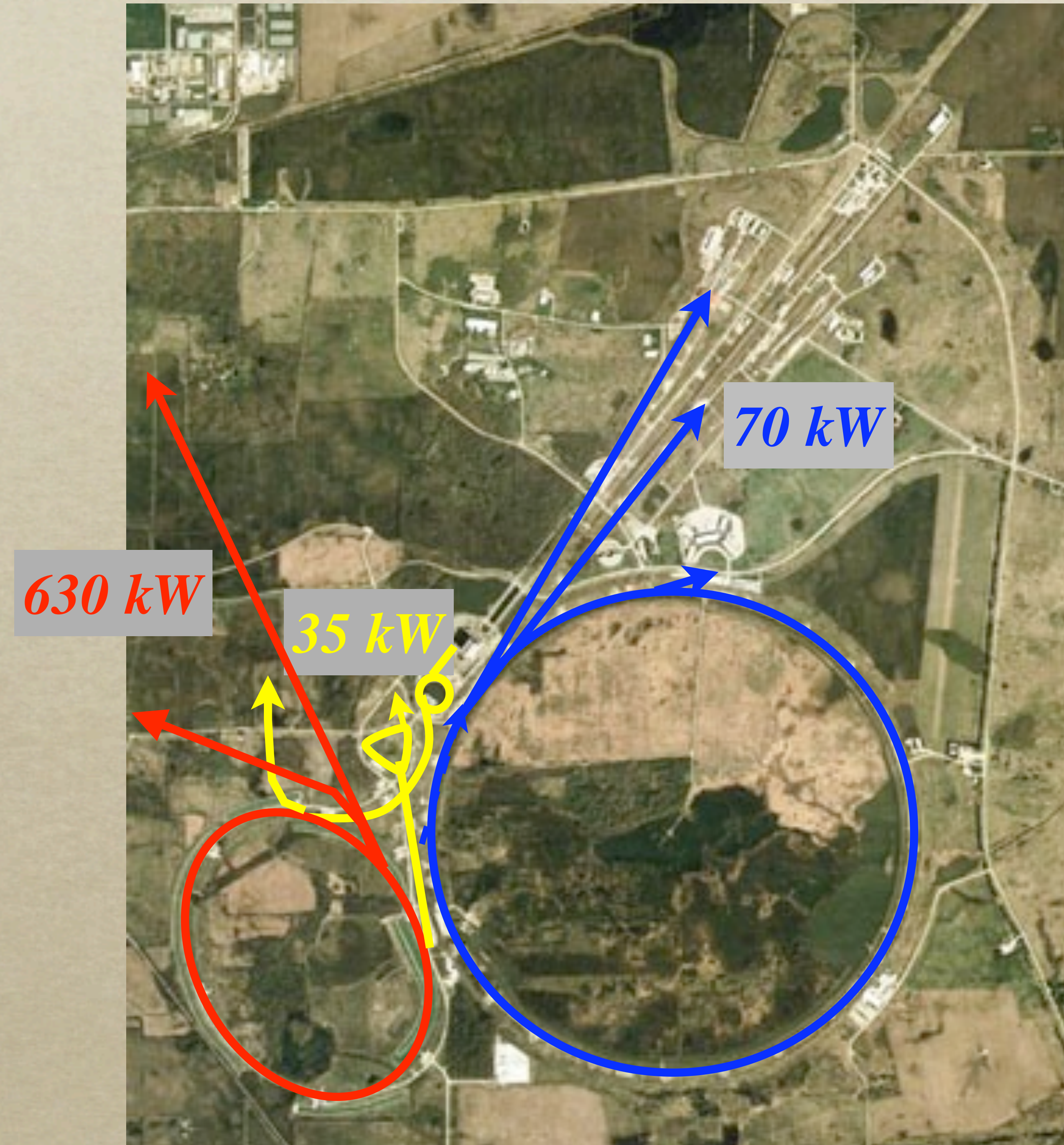
- *Accelerator meetings had been held nearly weekly prior to the Holiday season*
  - *~18 people involved from FNAL, UIUC, Boston*
- *Concentrating on*
  - *building requirements*
  - *target station, pion collection, decay region*
  - *transport from AP beam lines to g-2 storage ring*
  - *kicker and rf requirements*
- *Obviously not "project oriented" yet, but could quickly be developed along lines of Mu2e WBS*

Summary

- *Mu2e is approved with CD-0, working toward CD-1; g-2 has strong case, seeking final approval, looking for funding from DOE; Directorate and DOE are requesting further information regarding the kaon decay proposal*
- *Much on-going work to do: beam optics, scenario development, beam tests of extraction techniques, bunch formation, extinction measurements, ...*
- *With coordinated effort, can minimize costs to all experiments*
- *Could pave way for other experiments and/or R&D efforts using FT facilities*
    - *kaon program, muon cooling experiments, targeting R&D, ...*
- *Targeting R&D group would be a welcome addition to the lab and the community, taking advantage of our already expert staff and establishing a world-class group for on-going and future needs in the field*
- *AD organization will need to align itself and emphasize its strategic role in the Intensity Frontier efforts*

Proton Fixed Target Programs (*ca.* 2015)

- *Future Daily Operation*
  - *Run **NuMI/LBNE***
  - *Run **microBooNE, g-2, Mu2e, target R&D, EDM, muCool, ...***
  - *Run **MIPP, MTest, Drell-Yan, Kaon, ...***
- *Plus…*
  - *NML/ILCTA (A0)*
  - *HINS*
  - *Project X*
  - *...*



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